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Consistency of Paving Grade Asphalts At Various Temperatures

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16. ABSTRACT

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One of the important engineering properties of asphalt is the temperature susceptibility of the material over the range of temperatures encountered during mixing, laying and service life. The change in consistency over the temperature range encountered in the field is very large, and numerous empirical tests have been developed for measurements at various temperatures. Although these empirical tests provide valuable information, it is difficult to establish relations between measurements of one test at one temperature with another test at a different temperature.

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State of California
Department of Public Works
Division of Highways
Materials and Research Department

December 20, 1965

Lab Auth. 431338

Mr. J. C. Womack
State Highway Engineer
Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is:

FINAL REPORT ON

CONSISTENCY OF PAVING GRADE

ASPHALTS AT VARIOUS TEMPERATURES

Study by ....Pavement Section
Under general direction of ....E. Zube
Supervised by ....J. Skog & G. Kemp
Laboratory work done by ....Asphalt Group
Report by ....G. Kemp
J. Skog

JOHN L. BEATON
Materials and Research Engineer

Attach.
cc: CGBeer

State of California

Highway Transportation Agency

Memorandum

To : Mr. G. A. Hill
Planning
Attention C. G. Beer

Date: January 31, 1966

File : Lab Auth. 431338

From : John L. Beaton
Department of Public Works—Division of Highways
Materials and Research Department

Subject:

Attached are four copies of a final report entitled, "Consistency of Paving Grade Asphalts at Various Temperatures", submitted in accordance with Circular Letter 64-64.

This report was approved for distribution by L. R. Gillis, Assistant State Highway Engineer, Operations, on January 21, 1966.

Original Signed
JOHN L. BEATON
JOHN L. BEATON
Materials and Research Engineer

JS:EA
Att.

FORM WH-38 REV.

SYNOPSIS

The consistency of paving grade asphalts at various temperatures furnishes important information in connection with mixing, laying and service life of the asphaltic binder. Studies are presented on a falling plunger viscometer for measuring low temperature viscosities of paving grade asphalts. An analysis of the Cornelissen and Waterman scheme for determining the temperature susceptibility of an asphalt is also presented.

INTRODUCTION

One of the important engineering properties of asphalt is the temperature susceptibility of the material over the range of temperatures encountered during mixing, laying and service life. The change in consistency over the temperature range encountered in the field is very large, and numerous empirical tests have been developed for measurements at various temperatures. Although these empirical tests provide valuable information, it is difficult to establish relations between measurements of one test at one temperature with another test at a different temperature.

Recently, asphalt technologists have again become interested in measuring viscosity at various temperatures with instruments capable of providing results in absolute units, (poises). A number of viscometers of various types have been developed over a period of years for providing results in absolute units, but most of them are quite complex and expensive. However, during the past ten years relatively simple equipment has been developed for measuring viscosity in poises over a range of 60 - 350°F. At temperatures of 140 - 350°F capillary viscometers are practical and are now being proposed for use in specifications. In the range of 60 - 120°F the sliding plate microviscometer (1) provides satisfactory results in absolute units. The problem of measuring viscosity at lower temperatures still remains, and a rather intensive study is being performed by various organizations. Recently two instruments have been developed which appear to have promise as possible control instruments for low temperature measurements. The first is a modification of the existing Shell microviscometer technique (1) and the other is a new version of the Falling Plunger Viscometer (2). The Materials and Research Department has performed studies on the Falling Plunger Viscometer as developed by R. J. Schmidt and L. E. Santucci (2), and results of this work will be covered in this report.

The development of adequate equipment for determining consistency in absolute units, over the entire range of temperatures, has posed the problem of plotting the data to obtain the temperature susceptibility factor. Rather extensive studies have been performed on the development of a scheme for expressing viscosity-temperature relations over a large temperature range with viscosities varying from 10^{-1} through 10^{10} poises. An excellent summary of this work together with references is found in reference (3). According to the authors, one of the most promising schemes for expressing viscosity-temperature relationships is that proposed by Cornelissen and Waterman. This report will present our findings on the use of this equation.

CONCLUSIONS

Studies with a falling plunger viscometer for measuring viscosities at low temperatures indicate that the instrument is not satisfactory for routine control work.

The Cornelissen and Waterman scheme for plotting viscosity data over a large range in temperature does not produce a straight line relation for all California 85-100 grade paving asphalts used in the analysis. In other words, extrapolation to determine low temperature viscosities from a curve plotted from other viscosities at more elevated temperatures may not check, by a factor of 2 to 3, an actual measurement. There is a continuing need for further study on this subject.

RESULTS AND DISCUSSION

The Falling Plunger Viscometer

A falling plunger viscometer was constructed according to working drawings furnished by R. J. Schmidt of Chevron Research Corporation. Complete details including photographs and line drawings are shown in reference (2). Molten asphalt is poured in the space between a preheated inner plunger and outer cylinder. The annular space for the asphalt sample between the plunger and cylinder is 0.2 cm wide while the length of the space is 5.0 cm. When the asphalt is cooled, the ends of the plunger are cleaned, and the unit is transferred to a special holder in a temperature controlled water bath. The special holder is constructed so that movement of the plunger may be measured by water displacement. The water displaced during plunger movement from applied weights is followed by watching the movement of a small air bubble along a pipette. Movement of the plunger is plotted against time and the slope of the line is the rate of plunger movement for a specific load. Using this information the viscosity is obtained for any specific shear rate.

After preliminary testing a number of modifications were necessary. The first problem encountered in the original design was the Teflon mold top which warped so badly after three heatings in a 275°F oven that it had to be discarded because of leakage. This was remedied with two brass mercury amalgamated plates.

The measurement of plunger movement by means of an air bubble was not entirely satisfactory, and an Ames dial was attached to the instrument for this purpose.

Difficulty was encountered with the loading device assembly. Initially, it was difficult to align the heavy plates in order to prevent binding of the platform rod. This was eliminated by removing the eight inner nuts and substituting a sleeve over each leg between the plates, and replacement of the bronze bearings with linear Thompson ball bearings.

Low temperature viscosity tests were performed on a number of California 85-100 paving asphalts with the modified unit. These results were obtained on the original asphalt and on the residue after the Rolling Thin Film test, which simulates the hardening during field mixing operations. Determinations were made at 39.2°F and a 0.001 sec^{-1} shear rate. In the test the heaviest load was applied first in order to breakdown "structure" of the asphalt. Difficulty was encountered in using the authors recommendations to apply the light load first, since many of the asphalts were highly shear susceptible. The results on this test series are shown in Table A. In the case of California products, the viscosities at 39.2°F vary by approximately a factor of 2 to 3 for the 85-100 grade. When the comparison is made on the Rolling Thin Film residues the factor is below 2. It is interesting to note that some asphalts having a relatively high original viscosity may be quite low in the comparison scale after the Rolling Thin Film test. It would seem preferable to specify the low temperature viscosity after the Rolling Thin Film test, since this is the viscosity expected at the beginning of service life.

Based on our studies with the falling plunger viscometer, we would not recommend its use as a control instrument. Recently, we have used the modified plates for the Shell microviscometer in a cooperative viscosity study. These plates and the test unit appear to provide a more simple method for performing low temperature viscosity tests.

Viscosity-Temperature Relationship Between 39.2°F and 325°F

A satisfactory method for plotting viscosity results at various temperatures would permit one to determine viscosity at any temperature by two viscosity readings at two temperatures. These readings could be determined at elevated temperatures where the influence of shear susceptibility is not of great significance and instrumentation is quite simple. This is the present practice for determining the viscosity index of lubricating oil. However, many of the expressions proposed for lubricating oils are not applicable to asphalt because of the extremely wide range of viscosity over which asphalt is used.

According to R. L. Griffin (3), one of the most promising schemes for expressing viscosity-temperature relationships is that proposed by Cornelissen and Waterman which is based on a plot of log viscosity versus the reciprocal of the temperature raised to a variable exponent, the exact value of which is different for different types of liquids. Griffin (3) reported that viscosity data for a group of commercial asphalts covering the range 32°F to 285°F was quite well represented by a straight line when the value of the exponent X is 4. The finding of a straight line relationship also permits the calculation of temperature susceptibility by the following equation:

$$\text{Slope} = \frac{\log n_{T_1} - \log n_{T_2}}{\dfrac{1}{T_1^{\,4}} - \dfrac{1}{T_2^{\,4}}}$$

In order to test the Cornelissen equation as developed by Griffin, viscosities were determined at various temperatures on a series of California 85-100 grade paving asphalts. Viscosities at 275 and 325°F were determined with a standard cross arm capillary viscometer while those at 140°F were determined using a vacuum capillary unit. The sliding plate microviscometer was used for 77°F and the falling plunger unit for 39.2°F determinations. The results are shown in Table B.

The data, shown in Table B were plotted on a large scale chart using the Cornelissen and Waterman scheme. In all cases a plot of the viscosity values at 140, 225 and 325°F formed a straight line. However, when an attempt was made to extend this line to the measured value at 77°F the match was not satisfactory in all cases. The comparison of measured and extrapolated readings at 39.2°F are shown in Table C. In some cases the checks are quite good, but in others there is a variation by a factor of 2 to 3. The best explanation is the difference in shear susceptibilities of the various asphalts at temperatures below 140°F. The variation might be greater if asphalts from other regions were compared. We do not have an explanation for the difference in the findings of Griffin and those presented in this report. Griffin does not state the shear rates used for his viscosity determination at 77 and 32°F, which if different than used in this study, could lead to a different conclusion. On the basis of these studies, it appears at present that a viscosity determination must be performed at low temperatures for accurate results.

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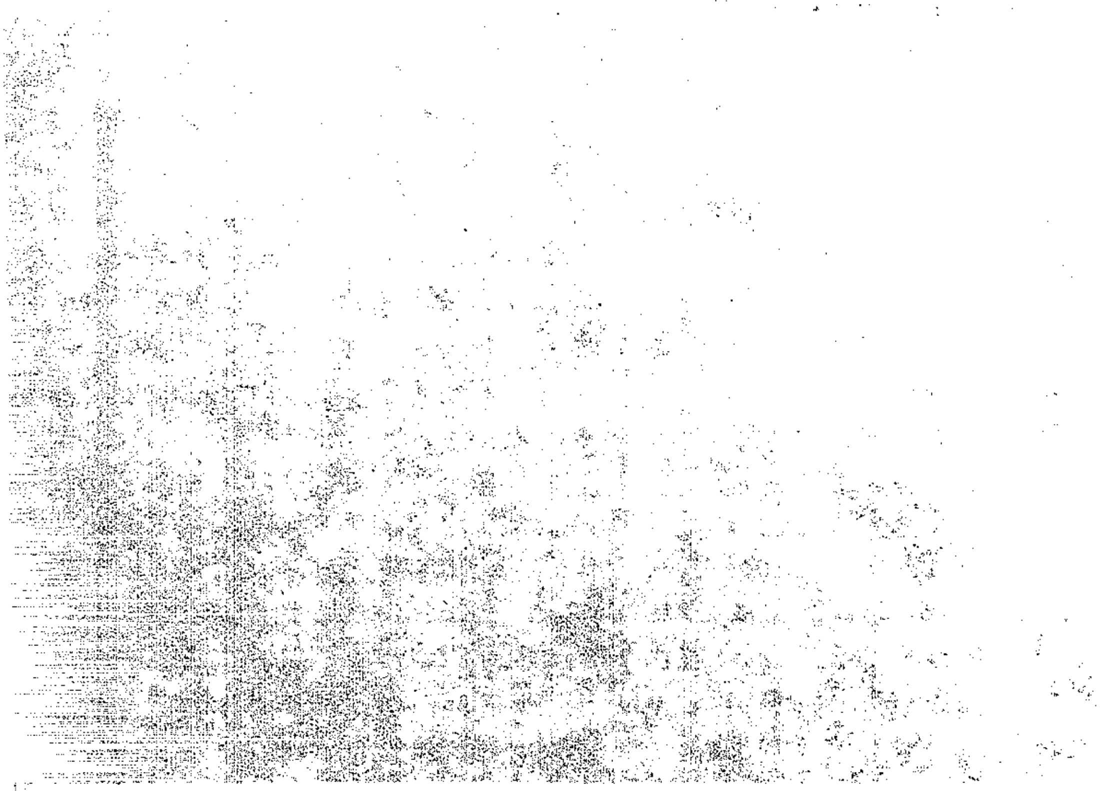

TABLE A

Viscosity Test Results at Low Temperature Using California 85-100 Grade Paving Asphalts

Sample No.	Code	Orig. Pen $77^{o}F$	Viscosity Poises X10^8 at $39.2^{o}F$* Original	After RTF Test	Viscosity Ratio $\frac{RTF}{Orig.}$
R 3620	A	96	4.20	16.70	3.98
R 3621	B	88	5.15	15.00	2.92
R 3622	C	99	7.25	19.20	2.65
R 3623	D	96	7.80	17.75	2.28
R 3624	E	90	5.60	15.20	2.72
R 3625	F	95	4.85	13.80	2.84
R 3627	G	90	6.00	11.90	1.99
R 3628	H	86	8.95	19.60	2.19
R 3629	I	105	3.35	17.50	5.23
R 3630	J	92	4.27	16.00	3.74
R 3631	K	92	5.80	11.30	1.95
R 3632	L	90	5.40	11.70	2.17
R 3640	M	91	9.20	13.00	1.42
R 3641	N	94	4.05	15.00	3.71
R 3642	O	93	7.45	11.10	1.49
R 3643	P	98	5.00	11.00	2.20
R 3656	Q	96	7.00	12.80	1.83

*Shear Rate = 0.001 Sec^{-1}

TABLE B

Viscosity Test Results For
Various California 85-100 Penetration Paving Asphalts

Sample No.	Code	Pen. at 77°F	Viscosity, Poises 325°F	225°F	140°F	77°F .001 Sec^{-1}SR	77°F .05 Sec^{-1}SR	39.2°F .001 Sec^{-1}SR
R 3620	A	96	.643	10.16	1.094×10^3	$.82 \times 10^6$	$.77 \times 10^6$	4.20×10^8
R 3621	B	88	.918	15.27	1.597×10^3	1.75×10^6	1.09×10^6	5.15×10^8
R 3622	C	99	.609	8.08	$.552 \times 10^3$	1.97×10^6	$.86 \times 10^6$	7.25×10^8
R 3623	D	96	.618	9.37	$.764 \times 10^3$	1.25×10^6	$.79 \times 10^6$	7.80×10^8
R 3624	E	90	.741	12.18	1.212×10^3	1.25×10^6	$.91 \times 10^6$	5.60×10^8
R 3625	F	95	.663	10.22	$.937 \times 10^3$	$.80 \times 10^6$	$.78 \times 10^6$	4.85×10^8
R 3627	G	90	.576	9.13	1.038×10^3	$.99 \times 10^6$	$.78 \times 10^6$	6.00×10^8
R 3628	H	86	.915	15.05	1.625×10^3	1.75×10^6	1.07×10^6	8.95×10^8
R 3629	I	105	1.191	19.45	1.915×10^3	1.64×10^6	$.98 \times 10^6$	3.35×10^8
R 3630	J	92	.753	12.88	1.378×10^3	1.23×10^6	$.95 \times 10^6$	4.27×10^8
R 3631	K	92	.570	9.03	$.999 \times 10^3$	$.89 \times 10^6$	$.81 \times 10^6$	5.80×10^8
R 3632	L	90	.675	10.96	1.179×10^3	1.37×10^6	$.89 \times 10^6$	5.40×10^8
R 3640	M	91	1.080	17.59	1.696×10^3	1.44×10^6	1.07×10^6	9.20×10^8
R 3641	N	94	.965	16.04	1.466×10^3	1.39×10^6	$.97 \times 10^6$	4.05×10^8
R 3642	O	93	1.045	16.45	1.534×10^3	1.11×10^6	1.02×10^6	7.45×10^8
R 3643	P	98	.582	8.79	$.969 \times 10^3$	$.76 \times 10^6$	$.71 \times 10^6$	5.00×10^8
R 3656	Q	96	.990	15.85	1.528×10^3	1.55×10^6	1.12×10^6	7.00×10^8
		Ave.	.796	12.74	1.264×10^3	1.29×10^6	$.92 \times 10^6$	5.96×10^8

TABLE C

Comparison of Extrapolated and Measured Original Viscosities at 39.2°F Through Use of The Cornelissen and Waterman Scheme

R No.	Code	Viscosity - Poises 39.2°F; S.R. = 0.001 Sec.$^{-1}$ Measured	Extrapolated Note 1	Extrapolated Note 2
R 3620	A	$4.2x10^8$	$3.7x10^8$	$2.6x10^8$
R 3621	B	$5.2x10^8$	$5.2x10^8$	$3.8x10^8$
R 3622	C	$7.3x10^8$	Not Possible	$4.5x10^7$
R 3623	D	$7.8x10^8$	Not Possible	$9.0x10^7$
R 3624	E	$5.6x10^8$	$5.6x10^8$	$2.8x10^8$
R 3625	F	$4.9x10^8$	Not Possible	$1.6x10^8$
R 3627	G	$6.0x10^8$	$6.0x10^8$	$3.5x10^8$
R 3628	H	$9.0x10^8$	Not Possible	$3.7x10^8$
R 3629	I	$3.4x10^8$	$3.9x10^8$	$3.7x10^8$
R 3630	J	$4.3x10^8$	$4.3x10^8$	$3.8x10^8$
R 3631	K	$5.8x10^8$	$5.0x10^8$	$2.6x10^8$
R 3632	L	$5.4x10^8$	Not Possible	$2.7x10^8$
R 3640	M	$9.2x10^8$	$6.5x10^8$	$4.0x10^8$
R 3641	N	$4.1x10^8$	Not Possible	$2.5x10^8$
R 3642	O	$7.5x10^8$	Not Possible	$2.8x10^8$
R 3643	P	$5.0x10^8$	$3.9x10^8$	$2.5x10^8$
R 3656	Q	$7.0x10^8$	Not Possible	$2.5x10^8$

Note 1 - Extrapolated from Viscosity Measurements at 77°F, S.R. 0.001 Sec.$^{-1}$; 140, 225 and 325°F

Note 2 - Extrapolated from Viscosity Measurements at 140, 225 and 325°F

STATE OF CALIFORNIA
HIGHWAY TRANSPORTATION AGENCY
DEPARTMENT OF PUBLIC WORKS
DIVISION OF HIGHWAYS

STATE OF CALIFORNIA · DEPARTMENT OF PUBLIC WORKS · DIVISION OF HIGHWAYS

A PRELIMINARY STUDY OF ALUMINUM AS A CULVERT MATERIAL

NOTE: This report is not to be used for advertising, publication, or promotional purposes.

August 1, 1964

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State of California
Highway Transportation Agency
Department of Public Works
Division of Highways

August 1, 1964

Lab. PWO No. 53097 R
Hdqtrs. Work Order
No. 64-19U51H17

Mr. J. C. Womack
State Highway Engineer
California Division of Highways
Sacramento, California

Dear Sir:

Submitted for your consideration is a report on:

A PRELIMINARY STUDY OF

ALUMINUM AS A CULVERT MATERIAL

Study made by	Concrete Section
Under general direction of . . .	D. L. Spellman
Work supervised by	R. F. Stratfull
Report written by	R. F. Stratfull

Very truly yours,

John L. Beaton

JOHN L. BEATON
Materials and Research Engineer

cc: LRGillis
JEMcMahon
CGBeer
ACEstep
JFJorgensen
ELTinney
HCMcCarty
ALElliott

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A PRELIMINARY STUDY OF

ALUMINUM AS A CULVERT MATERIAL

I. Introduction

The possibility of an economic or engineering advantage in the use of aluminum as a culvert material has resulted in this investigation by the California Division of Highways in co-operation with the Bureau of Public Roads.

The investigation was initiated on March 31, 1961, under Laboratory Project Authorization 71-R-6244 and more recently under R-53097. The cost of the investigation has been borne by the California Division of Highways and the Bureau of Public Roads. The actual investigation and associated tests were performed by the Materials and Research Department of the California Division of Highways. This work supplements previous investigations of culvert materials.

This report not only contains information on the field performance of test culverts, but also includes the results of laboratory testing and presents recommendations for the use of corrugated aluminum pipe.

II. Summary and Conclusions

For the most part, nearly all of the test sites used in this preliminary study can be termed as "highly aggressive", as determined by Test Method No. Calif. 643 which includes criteria for classifying the aggressiveness of the environment. They were chosen to provide a maximum amount of field experience in a minimum amount of time. Therefore, the numerical test results obtained from this investigation must be regarded as qualitative and subject to modification by experience.

In general, the data obtained during this investigation agree with the published literature in that aluminum does not seem to be chemically attacked when the pH of the solution is near neutral (7.0).

These, and other published data, agree that within the limits of pH 6.0 to 8.0, aluminum should be chemically stable providing there are no other controlling factors such as:

1. Waters containing heavy metals
2. Concentration-cell corrosion
3. Stagnant or quiescent water
4. Waters containing large quantities of dissolved chemicals

It is believed that these foregoing factors can be successfully controlled by requiring an aluminum culvert protected by means of a bituminous or other approved organic type of coating.

At the pH ranges of 5.0 to 6.0, and 8.0 to 9.0, the chemical stability of aluminum does not appear to be as clearly defined as when the pH range is 6.0 to 8.0. Therefore, whenever aluminum culverts are to be used in the environmental pH ranges of 5.0 to 6.0, and at 8.0 to 9.0, they should always be protectively coated.

This investigation did not determine any direct relationship between the resistivity of a soil or water and the corrosion rate of aluminum.

Published data indicate that at those locations where

the in-place soil resistivities were less than 1500 ohm cm, the corrosion of an aluminum pipeline was controlled by the application of cathodic protection. Also, published aluminum culvert test results based on observations over a maximum of 3.5 years of exposure, indicated that corrosion from the flow was observed to be almost nil when the in-place soil or the water resistivity had a mean value of approximately 3100 ohm cm. Other reports have indicated that aluminum has been attacked when the water contained more than 181 parts per million of calcium carbonate.

On the basis of the foregoing, it is apparent that a resistivity limitation is required because it is a guide to the relative chemical content of the environment.

For unpaved cross-drains, it is recommended that aluminum metal not be used when the minimum resistivity is less than 2000 ohm cm. This value implies that the total dissolved solids in the water or soil is approximately 450 parts per million, which can include a total of approximately 125 parts per million of sulfates as SO_4 and chlorides as Cl ions.

In culvert locations which are not as economically critical as cross-drains, a reduction in the pH and resistivity limits could be made so as to gather further experience with this material.

The test results of this investigation indicate that aluminum is sensitive to abrasion. In fact, the corrosion-inhibiting cladding on the aluminum specimens was penetrated in all of the laboratory corrosion-abrasion tests. The specimens in this test had a velocity of 5 fps, and the abrading material was Ottawa sand. The field data agree with the laboratory tests that aluminum is not as abrasion resistant as a steel culvert. Therefore, at this time, it appears necessary to restrict aluminum from indiscriminate use in streams of high flow velocities containing an abrasive bed load.

This investigation also indicates that flow velocity per se may not be a controlling factor in the abrasion process. It appears that the degree of abrasion suffered by a culvert will not only be a function of the velocity, but also of the size, quantity and shape of the bed material. Severe abrasion was observed in the test culvert where the bed contained shattered and angular rocks. Conversely, at another culvert site with similar calculated flow velocities, a minor amount of abrasive destruction was observed where the material consisted of rounded boulders.

On the basis of this accelerated investigation it is estimated that under favorable conditions, aluminum may have a

service life up to an estimated 25 years. However, the durability of the material should be continuously verified so as to confirm or modify the recommendations since they are partially based upon laboratory data.

III. Recommendations

It is recommended that the durability of aluminum culvert material be continuously monitored so as to confirm or modify, through added field experience, the culvert use recommendations that are shown in the following table "Recommended Use of Minimum Gage Thickness of Corrugated Aluminum Pipe for Anticipated 25-year Maintenance-free Service."

RECOMMENDED USE OF MINIMUM GAGE THICKNESS CORRUGATED ALUMINUM PIPE
ANTICIPATED 25-YEAR MAINTENANCE-FREE SERVICE

			Flow Conditions [2]							
			Less Than 5 FPS		Less Than 7 FPS		Greater Than 7 FPS			
Location	Protective Coating[1]	pH Range	Abrasive	Non-Abrasive	Abrasive	Non-Abrasive	Abrasive	Non-Abrasive	Continuous Flow	Resistivity Ohm cm. (Min. Value)
Overside drain	None	6-8	X	X	X	X	No	X	X	2000
	Bituminous	5-9	X	X	X	X	No	X	X	1500
Under drain	None	6-8	X	X	X	X	No	X	X	2000
	Bituminous	5-9	X	X	X	X	No	X	X	1500
Side drain	None	6-8	X	X	X	X	No	X	X	2000
	Bituminous	5-9	X	X	X	X	No	X	X	1500
Cross drain	Bituminous	6-8	X	X	No[3]	X	No	X	No	2000
	Bituminous Plus paved Invert	5-9	X	X	X	X	No[3]	X	X	None

Notes:

[1]When pipe is bituminously coated, backfill to have pH of not less than 5.0 and no resistivity limitation.

[2]"X" in column denotes recommended use.

[3]May be used if metal gage thickness is increased by 2 numbers over minimum loading requirements.

Subject to approval, other thin film type of di-electric coatings may be used in lieu of a thin film bituminous coating.

Aluminum is not to be used as a section or extension of a culvert that contains steel sections.

In areas where the flow contains heavy metals, aluminum shall not be used unless the invert is paved, irrespective of the pH and resistivity.

IV. Factors that Influence the Corrosion of Aluminum in Soils or Waters

A. Hydrogen-ion Concentration, pH

It has been reported that barring an actual test, aluminum alloys are unsatisfactory for use when the pH of the solution is greater than 10 or less than 3.[1] Other reports have indicated that aluminum is generally inert or inhibited from accelerated corrosion when the pH range of the environment is: 4 to 9[2], 6 to 8[3,4], 5.5 to 7.8[5], 4 to 8[6], and 4.5 to 9[4].

Based upon the standard free energies of the constituents, and the deduced electrochemical behavior of aluminum, the oxide of the metal (hydragillite, $Al_2O_3.H_2O$) is theoretically chemically stable within a pH range of 4 to 8.6, providing the solution is free of substances which can form soluble complexes or insoluble salts of the metal.[5]

As indicated by the foregoing, it is apparent that aluminum is chemically stable in the near-neutral range of pH (7.0). However, it has been emphasized in the literature that the pH of a solution or soil is not the primary control, or a completely reliable basis for predicting the chemical stability of aluminum.[2,3,7,8]

From the preceding, it is apparent that the knowledge of the pH of a solution or soil can be a valuable tool in predicting the durability of aluminum, but other factors must be considered.

Because of the relatively long service of steel culverts and pipe, the relative influence of the pH of the environment to the rate of corrosion of this metal has been determined. (References 10,11,12,13.)

B. Chemicals

It has been reported that in sodium carbonate solutions of greater than 0.001 normal concentrations (approximately 60 parts per million), aluminum is significantly attacked.[9] When the mineral acid concentration is less than

0.001 normal, aluminum is resistant to corrosion.[9] In acid solutions containing only one anion, the rate of corrosion increases in the following order: (1) acetate, (2) phosphate, (3) sulfate, (4) nitrate, (5) chloride.[9]

The presence of heavy metals, copper, mercury, cobalt and nickel in waters have been reported as a cause of the corrosion of aluminum.[1,3,4,8]

Aluminum which does not have the highly corrosion resistant cladding has been observed to have accelerated corrosion when a water contains 0.09 ppm of copper, 0.08 ppm cobalt, and 0.03 ppm nickel.[3]

It has been generally observed that aluminum corrodes in "hard" waters. Although no correlation was determined between the relative hardness of a water and the corrosion rate of aluminum, the reported data indicate that a "hard" water contains approximately 180 parts per million or more of carbonates that are calculated as calcium carbonate.[8] Of the nine tests of aluminum in different natural waters containing more than 180 ppm of hardness, seven of these samples were found to have a pit depth of 40 mils in less than 6 months.[8] The greatest reported concentration of copper found in the survey of these seventeen natural waters was 0.11 ppm.[8]

From the preceding data, it appears that either a complete chemical analysis should be made of the soils or waters to which aluminum would be exposed, or an economical means for testing these environments for mineral content should be considered.

C. Electrical Resistivity of the Environment

The electrical resistivity has been found to be an indicator of the relative concentration of chemicals in a soil or water.[10,11] The greater the electrical resistivity, the less the concentration of soluble chemicals.

Generally, no correlation has been found between relative values of resistivity and an associated corrosion rate of aluminum.[2]

It was reported in the literature that on one underground gas pipeline, "hot spot" cathodic protection was applied to those sections of the pipe which were embedded in a soil with a resistivity of less than 1500 ohm cm.[14]

Based upon the preceding lack of data, it appears that the electrical resistivity of an environment is thus far only of academic interest with regard to inferring a possible corrosion rate of aluminum. The electrical resistivity of an environment may be of use when considering that it is an indicator of the highly mineralized solutions which can cause the corrosion of aluminum and steel.

The chemical contents in ppm of solutions and soils may be estimated by the following formulae:

$$\text{Total dissolved solids} = \frac{900{,}000}{R} \quad \ldots\ldots\ldots \quad (1)$$ [18]

$$\text{Sum of Sulfates and Chlorides } (SO_4+Cl) = \frac{784{,}000}{R^{1.15}} \quad \ldots\ldots\ldots \quad (2)$$ [11]

Where R = resistivity in ohm cm.

D. Bi-metallic Corrosion

When aluminum is electrically connected to steel, approximately 1.2 volts can be initially developed and can result in an accelerated corrosion rate of the aluminum.[15,16] Aluminum has been used as a sacrificial anode for galvanically inhibiting the corrosion of steel.[17]

The degree of galvanic corrosion of an aluminum culvert would be considered minor if the steel in contact with the aluminum were limited to just a bolt. Conversely, if the situation were reversed with an aluminum bolt in a steel culvert, the aluminum could rapidly corrode.

From this, it is obvious that judgment must be exercised when coupling dissimilar metals to aluminum. A steel bolt used in a culvert band coupler would not seriously affect the aluminum culvert. The intermixing of steel and aluminum culvert sections should not be done as there could be rapid corrosion of the aluminum over an extensive area. The zinc on a galvanized steel culvert is generally anodic and will generally corrode when electrically coupled to aluminum in most neutral or acid solutions. Once the zinc is gone, the steel then can cause the aluminum to corrode.

[illegible] directly [illegible]

[illegible] carefully designed, and can result [illegible]

[illegible] for [illegible] satisfactory [illegible]

[illegible] an ultimate [illegible]

[illegible] contact with [illegible]

[illegible] would be seriously [illegible]

E. Concentration Cell and Crevice Corrosion

Concentration cell corrosion is generally defined as an electrolytic corrosion cell which is caused by a difference in the concentration of the electrolyte, or differences in the concentration of metal ions in solution.[1,16]

In effect, a concentration cell can be the initial cause of corrosion, or, as a result of corrosion started by other causes,[1] it can be the mechanism by which the corrosion process can continue.

Crevice corrosion is generally considered as a corrosion cell which is the result of differential aeration of the solution.[1] A crevice type of corrosion cell can result in severe corrosion of the aluminum because the voltage of an active/passive cell can be superimposed upon the voltage of the differential aeration cell.[1] Although structural steel is greatly affected by differential aeration corrosion cells,[16] it is unlikely that this metal could be generally susceptible to what is commonly called an active/passive corrosion cell in the normal soil or water.[19]

In general, the aggressive types of corrosion cells may be caused to form on aluminum by the following factors:

1. Bolted or riveted construction[1,20]
2. Pockets or locations of liquid entrapment[1,20]
3. Non-uniform soil compaction[2]
4. Differential aeration[1]
5. Stagnant pools of water[21]
6. Electrical connection to ferrous metals[16,20]

V. Current Results of Field Tests

The test results of the eight field test culvert installations are shown in detail on the attached Tables 1 through 3, and pictorially on Figures 1 through 23. These test sites were chosen because some are the most highly corrosive and abrasive conditions to which an actual highway culvert will and has been placed. This was a means of getting accelerated results. An exception to this was the culvert at I-Hum-35-C, which is in the northwestern part of California near Bridgeville. This latter culvert site is exposed to the environmental conditions which are typical for the geographic area and are only considered to be moderately aggressive.

A. Abrasion Test Results

The details of the results of the comparative field abrasion tests are shown on Figures 1 through 3 and on Figures 7 through 11 inclusive, and also on Tables 2 and 3. Specifically, the culverts located at (1) I-Hum-35-C, and (2) IV-SCl-5-C, are the only culverts which could be considered to have an abrasive environment. From past experience, the former culvert (1) is only considered an average abrasion culvert, and the latter (2) is known to be highly abrasive.

As shown on Tables 2 and 3, the rate of metal loss of the aluminum indicates that it will perforate by abrasion in approximately one-tenth the time as a steel culvert.

At periods of a high yearly flow, both abrasion test culverts carry a bed load of rocks. However, the flow velocity at the test culvert at I-Hum-35-C would range from 10 to 14 feet per second, or about half the velocity at the other site. Because of the apparent two to one difference in the calculated flow velocities, it would be tempting to assign this velocity difference as the cause of the approximately 30:1 difference in severity of abrasion damage to the two culverts.

Although not a part of this program, an investigation of a culvert condition was made in the mountainous vicinity of Redding. This particular 48-inch diameter galvanized steel culvert was observed to have minor abrasion damage after approximately 7 years of service.

Cobbles of approximately 6 inches in diameter were observed lying in the invert at the outlet end of this pipe. The calculated flow velocity in the pipe is in the range of

20 to 25 feet per second.

The reader should be aware that the test results of erosion are exceedingly difficult to explain and objectively formulate to a mathematical certainty. For instance, the severly damaged test pipe located at IV-SC1-5-C may have had a calculated flow velocity in the range of 25 - 30 feet per second with a bed load of shattered rocks. The minor abrasion damaged culvert near Redding, California, (II-Tri-20-A, Sta. 582+73) has a calculated flow velocity in the range of 20 to 25 feet per second, and has a bed load of rounded boulders. Therefore, it is obvious that even though flow velocities are highly important, the size and shape (rounded or shattered) and hardness of the bed material may be of greater consequence in the subsequent degree of abrasion of a culvert.

For all practical purposes, no commonly used culvert coating or material would offer a maintenance-free service life at the highly abrasive test site, IV-SC1-5-C.

B. Corrosion Test Results

The details of the corrosion test results are shown on Tables 1 and 2, and Figures 1 through 6, and 12 through 23. Even though some of the test sites are regarded as being highly corrosive to steel, only three sites had a pH of less than 4.5, and the remaining five culverts were installed in sites with a pH range of 4.5 to 8.3. In effect, one-half (4) of the culverts were subjected to a flow or soil which had a pH that ranged between 6.6 and 8.3. For all seven comparative corrosion test culverts, the field test data indicate that on the average, the aluminum will be perforated by corrosion in approximately one-half as many years as galvanized steel.

For the five test sites in which the pH of the soil or flow ranged between 4.5 and 8.3, the data again indicated that aluminum would be perforated by corrosion in approximately one-half as many years as galvanized steel.

As shown by the attached photographs (Figures 1 through 23), the removed sections of aluminum are not generally attacked by small areas of random pitting, but at large areas of the pipe surface. Therefore, the corrosion is not considered to be the result of a minor and localized imperfection in the protective oxide film on the surface of the aluminum. Instead, the appearance of the large areas of corrosion on the soil contacting surface of the pipe, inside the laps, around the rivet holes, and beneath silt, strongly suggests that the corrosion is

the result of a concentration cell. This concentration cell appears to be the result of the soil causing a partial shielding of the metal from oxygen and in one case (XI-Imp-187-F), further complicated by the result of a differential concentration of soil salts in direct contact with the culvert.

With the exception of the culverts carrying the highly acid runoff, the corrosion attack of the aluminum was most severe on the backfill side of the pipes and in the joints.

VI. Laboratory Tests

A. Corrosion-Abrasion Test

In an attempt to compare the relative corrosion-abrasion resistance between galvanized steel and aluminum, these metals were separately exposed to solutions of various pH and resistivity. The testing equipment (dubbed the "wash machine") is shown on Figure 24. In each test, four each of the 4x8-inch similar metal specimens were clamped so as to rotate with the drum at a speed of approximate 5 fps. These specimens were electrically isolated from direct metallic contact to the drum by means of rubber spacers attached to the ends of the specimen. In addition, electrical isolation was further accomplished by the plexiglas multipurpose observation and access windows which were also used to clamp the samples in place during the test.

Prior to testing, all specimens were degreased with benzene, washed and scrubbed with soap, and then thoroughly rinsed with Sacramento city tap water.

Some pilot testing of galvanized steel indicated that within the normal testing period (approximately 8 days), the corrosion rate of this composite material would change so rapidly with time that each test would probably require more than two weeks. Therefore, to expedite results, the zinc was pre-stripped from all galvanized specimens with a solution of hydrochloric acid which was chemically inhibited from attacking the steel.

The details of the chemicals, etc., used in this test are shown on Table 4.

(a) Test Results - Corrosion

The details of the corrosion-abrasion tests for each metal are shown on Tables 5, 6, and summarized on Table 7.

On these tables, it will be observed that the extrapolated years to perforation are presented on the basis of four types of measurements, which are:

1. Maximum cross-section loss

2. Just the abrasion surface, or the upstream side of the corrugation which had initial contact with the sand

3. The corrosion surface which is any section of the corrugation except the abrasion surface

4. By means of 100 percent weight loss of the specimen

In general, these laboratory corrosion tests with the highly aerated solutions, indicated that the aluminum will take approximately twice as long to be perforated by corrosion as would be the plain steel.

Because of the corrosion characteristics of these two metals, it would be expected that aluminum would not be as adversely affected by an aerated solution as would steel.

Disregarding the resistivity of a solution, the data shown on Figure 25 indicates that steel could rapidly corrode in aerated solutions where the pH is less than approximately 5.0 and greater than 7.0. However, in the case of steel, it is misleading to infer that steel has its greatest corrosion resistance when it is subjected to an environment with a pH range between 5.0 and 7.0. Further analysis of these data show that for the steel test series, the pH of the solution is an important factor in the corrosion rate only when the pH is less than approximately 7.3. At pH values of less than approximately 7.3, the resistivity and the pH of the solution are the controlling factors. At greater pH values (7.3 or greater), the resistivity is the primary control of the relative corrosion rate of steel.

The data shown on Figure 26 indicates that aluminum is more resistant to corrosion in the pH range of approximately 5.5 to 8.5. An analysis of the data did not indicate any clear-cut trend in the influence of resistivity on the rate of corrosion. It is suspected that the aluminum was more sensitive to the types of chemicals rather than to the concentrations of the different chemicals used in this test.

Figures 27 and 28 are shown to depict the accuracy in reproducing a single type of test. From the data shown on these two charts, it is obvious that the individual test results probably have a test accuracy of ± 20%.

All of the reported test data were extrapolated on a straight line proportional basis to the particular end point;

i.e., metal perforation or 100 percent weight loss. Such methods of extrapolation of data are not recommended as being highly accurate, but are a means for comparison of test results. An equation which includes a factor of decreasing rate of corrosion with time, was not used. Therefore, these data infer an exaggeration of the numerical difference of the corrosion rates which were measured at the end of each test.

Since equations are available which include a factor describing the decrease in the corrosion rate with time, Figure 29 shows that there is a choice of three for steel(24,25,26) and one for aluminum.(8)

Figure 29 should not be construed to indicate that the corrosion rate of one metal is clearly less than the other. This is because the required constant for each equation may be manyfold greater or less than the other. Therefore, when the constants are included in the equations, the result could be that one metal may perforate in a few days, while the other metal may require years to perforate.

(b) Test Results - Abrasion

Figures 30 and 31 are shown to depict the appearance of plain steel and aluminum when corrosion was practically absent. In all tests, there was no noticeable wear on the abrasion surface of the steel. The abrasion surface is the upstream surface of the corrugation. Generally, the steel pitted on the abrasion as well as on other surfaces of the steel.

The typical loss of the aluminum cladding on the abrasion surface after an average of 8 days of testing is shown on Figure 31. It may be of interest to note that at the conclusion of Test No. 32 (36 days), the face of the sheared leading edge of the aluminum test panels peeled back for a distance of approximately 1/16-inch as a result of the impact of the specimen with the Ottawa sand at a velocity of approximately 5 fps.

After the mounting and polishing of all metallographic specimens, the steel was etched for 30 seconds with a solution of nitric acid (HNO_3) and amyl alcohol ($C_5H_{11}OH$). The aluminum specimens were etched for approximately 10 minutes with concentrated sodium hydroxide ($NaOH$) solution.

B. Continuous Submersion

The results of this laboratory test are shown in

detail on Tables 8, 9 and 10, and also on Figures 32 through 35.

The corrosion rate of the metal in this test was determined by micrometer measurements rather than by metallographic analysis. Basically this test consisted of submerging duplicate specimens of either riveted aluminum or riveted galvanized steel metal in a plastic container containing the described test solutions. There was no intermixing of galvanized steel or aluminum in any container. Both metals were culvert stock and were riveted by a commercial culvert fabricator. The culvert sheet metal and rivet materials are those which are commercially specified as culvert stock.

The pH and resistivity of the solutions were maintained to the proper level by periodic additions of the chemical additives. After the first 30 days of test, all of the solutions were replaced with a fresh test solution. There was no stirring or attempt to aerate the test solution.

An effort was made to have the test specimens in a quiescent water which would be similar to that found in bogs or marsh areas. Also, the resistivity was kept at a constant value of 1000 ohm cm. On the basis of steel corrosion, a solution resistivity value of 1000 ohm cm is generally not considered as being highly corrosive, but it is also not disregarded as being non-corrosive.

As shown on Figure 32, in all cases the zinc on the galvanized steel is intact and there is no corrosion of the underlying steel after 70 days of testing.

Figures 33, 34 and 35 show that in all cases, the aluminum was attacked at the metal laps, edges of the plate, near the rivet hole, and sometimes at scratches and also sheet rolling marks due to the corrugating process.

The over-all corrosion of the aluminum was less in the solution of pH 7.5 than in the 4.3 and 9.0.

The results of this test indicate that among other variables, a concentration cell type of corrosion attack is a common denominator in the causes of corrosion of aluminum in a quiescent solution. Also, aluminum can aggressively corrode in solutions of pH 4.3 and 9.0.

C. Laboratory Test in the Fog Room

The fog room used for this laboratory test is a

concrete curing room which is maintained at approximately 73.4°F and 100% relative humidity by means of temperature controls and water fogging equipment. The fog room can be construed as a misnomer as droplets of water are continuously being dispersed throughout the chamber which feels more like rainfall.

The pH of the atmoized water is 8.2 and the resistivity is 6300 ohm cm.

Figure 36 shows the appearance of galvanized steel after approximately one year of testing and the zinc is intact. Also shown on Figure 36, is the typical result of 117 days and also 94 days of exposure of the riveted aluminum samples to the fog environment. In this case, it will be noted that the aluminum has been attacked near the rivet hole, cut edges where the plates were in contact and also at the line where the two pieces overlapped. Apparently this corrosion attack is the result of a concentration cell.

By means of a micrometer, the depth of corrosion was determined and extrapolated on a straight line-proportional basis to a calculated time to perforation. The results of these measurements are shown on Table 11.

VII. Other Field Tests of Aluminum Culverts

An excellent and comprehensive study of the field performance of aluminum culverts was reported to the Highway Research Board by Messrs. T. A. Lowe and A. H. Koepf at the January 1964 meeting.[2] Although the authors did not report any rates of corrosion, they did include their observations on the appearance of the culverts. The reported condition of the pipes visually ranged from an unaffected condition to the extreme where the pipe wall was perforated. In many cases, the resistivity of the in-place soil or flow and also the pH was tabulated.

As the authors indicated in their report, it is obvious that the majority of the reported installations had no problems involving corrosion because approximately 60% of their data indicate that the visual condition of the culvert was unaffected or the metal was stained. It is assumed that stained aluminum is not evidence of corrosion and indicates a relatively unaffected condition.[3]

The authors[2] did not mathematically present their findings regarding the influence of soil pH or resistivity on the corrosion rate of aluminum. However, there appear to be some general mathematical relationships which could be of value.

For instance on Table 12, the reported condition of the culverts has been listed in an assumed rank of corrosion severity that varies from unaffected to perforated. In ranking the relative condition of the culverts, the more severe condition noted was arbitrarily assigned to represent the rank of the culvert. For instance, if the culvert was reported as "mottled stain. No attack. Random pitting of clad in invert", this culvert was assigned to the "pitting" classification on Table 12. For each of these culvert conditions, the acidic pH's of less than 7.0 were arithmetically averaged. The same was true of pH's that were greater than 7.0. In addition, the least resistivity of the in-place soil or water were averaged on the basis of the computed geometric mean[27] which is:

$$\text{Geometric mean} = \sqrt[n]{X_1 X_2 \ldots X_n} \quad \ldots\ldots\ (1)$$

n = number of observations

X = observed value

The geometric mean of the resistivity values was used because of the extremes in values that are normally found in resistivity measurements.

Although the validity of this analysis of data shown on Table 12 has not been verified, it is interesting to note that there seems to be a reasonably implied correlation of the data. This is implied by the observation that the severity of corrosion increases with decreasing pH and resistivity.

In the subject H.R.B. report[(2)], it was stated that their extensive experience has indicated that if aluminum is not attacked by corrosion after periods of a year or more, then the aluminum metal may be considered to be relatively inert to the environment. Conversely, it should also be true that if significant corrosion of the aluminum occurs at an early exposure period, then aluminum should sustain some rate of corrosion until disintegration.

From the data shown on Table 12, it appears that the anticipated performance of aluminum could be satisfactory when the pH ranges between 6.0 and 7.8. It is highly probable that when the pH of the environment exceeds these values, the aluminum could corrode at a rate that would vary from minor to severe.

The resistivity measurements shown on Table 12 were determined for the most part on an in-place soil. Therefore, they may not be accurately reproducible owing to the fact that these values are highly dependent upon the seasonally variable moisture content of the soil.

Normally, soil resistivity measurements used in culvert corrosion technology are based upon the minimum value. The minimum resistivity is normally less than the in-place soil resistivity. Therefore, care should be exercised when directly comparing the in-place field values to the minimum resistivity of a soil.[(10)]

VIII. Discussion

There is a small amount of published data concerning the service life of aluminum when used underground or as a culvert. The longest reported service life for this material as a culvert is 3.5 years.[2]

For underground applications of aluminum pipe, reports of up to 15 years have been published.[22] As reported, the 388 total miles of aluminum pipeline with an estimated average of seven years of service, only 8 - 9 miles have had to be replaced because of corrosion. None of the failed pipe was coated or received cathodic protection. Of this total reported pipe length of 388 miles, approximately 25% of its total length is protectively coated. In addition, approximately 30% of the total length of the pipelines received cathodic protection. Cathodic protection was not necessarily applied to coated pipe. The reported wall thickness of these pipelines varied from an equivalent corrugated metal pipe gage of approximately 16 to a reported maximum which would be approximately equivalent to 8 gage thickness. The number of thin gage pipe wall thickness was in the minority.

The review of the literature shows that some aluminum facilities have corroded when placed underground or as a carrier of water. Except for broad generalities, specific criteria for predicting the service life of aluminum as a culvert are not available.

Past experience with the use of galvanized steel culverts without a means for estimating service life, resulted in 63% of all of the culverts (7000) in just one of the eleven California highways districts needing replacement or repair within 30 years of service.[23] From this past experience, it is obvious that caution has to be exercised before a material should be allowed to be randomly used in large quantities on highway projects.

Because of the concentration-cell type of corrosion which has been observed in the laboratory and on the backfill side of the culverts in the field test sites, no aluminum cross-drains should be placed in critical locations without being bituminous or otherwise protectively coated.

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TABLE 1

Field Site Test Data

Locations	I-Hum-35-C Bridgeville	II-Sha-3-B Redding	III-But-21-B Oroville	IV-SCl-5-C Los Gatos	IV-SCr-5-A Scotts Xing	X-S.J-53-C Rio Vista	XI-S.D-2-Nat.Cty Sweetwater Br.	XI-Imp-187-F Salton Sea
Installed	8-20-61	11-16-61	8-21-61	10-19-61	10-3-62	8-16-61	9-26-61	9-29-61
Last Inspection	8-21-63	5-2-63	5-3-63	3-4-63	8-16-63	1-30-64	5-21-63	5-22-63
Yrs. Test Time	2.0	1.5	1.7	1.4**	0.83*	2.4	1.7	1.7
Average pH	6.6	3.3	2.7	7.7	3.7	4.5-6.3	8.3	7.5
Min. Resistivity	2500	650	165	3500	330	620-973	39	6.5
Na +K (as Na) PPM	----	14	7	65	---	178	12300	99740
Ca "	----	44	266	102	470	65	170	12300
Mg "	----	88	328	19	---	26	504	2170
CO_3 "	----	Nil	Nil	Nil	Nil	Nil	Nil	Nil
HCO_3 "	----	Nil	Nil	204	---	9	170	180
Cl "	----	Nil	50	516	26	144	14920	41520
SO_4 "	----	996	13800	132	2246	356	2220	7920

Note: * Steel CMP was in place approximately 1 year prior to installation of aluminum test pipe.

** This installation was removed during the last inspection.

Table 2

Culvert Site Test Results [1]

Location	Metal	Time in Test, Years	pH	Minimum Resistivity Ohm cm.	Estimated Years to Perforation Based on Metal Loss at: [2]			
					Minimum X-Section Loss	Upstream Surface of Corrugation		Downstream Surface or Valley of Corrugation (Corrosion Surface)
						Abrasion	Pitting	
I-Hum-35-C	Steel	2.0	6.6	2500	6.1	41	6.4	18
	Aluminum				3.6	3.6	---	6.9
II-Sha-3-B	Steel	1.5	3.3	650	2.3	----	---	2.3
	Aluminum				0.33	----	---	0.33
III-But-21-B	Steel	1.7	2.7	165	0.56	----	---	0.56
	Aluminum				0.56	----	---	0.56
IV-SCr-5-A	Steel	0.83	3.7	330	No test culvert			
	Aluminum				0.83	----	---	0.83
IV-SC1-5-C	Steel	1.4	7.7	3500	1.3	1.3	---	-----
	Aluminum				0.14	0.14	---	-----
X-S.J-53-C[3]	Steel	2.4	4.5 to 6.3	620 to 973	49	----	---	49
	Aluminum				12	----	---	12
XI-Imp-187-F[3]	Steel	1.7	7.5	6.5	6.7	----	---	6.7
	Aluminum				12	----	---	17
XI-SD-2-Nat.Cty[3]	Steel	1.7	8.3	39	25	----	---	33.
	Aluminum				4.8	----	---	6.6

1 All test results are based upon metallographic analysis of culvert samples.

2 Estimated years to perforation for all samples were calculated on the basis of a 16-gage metal thickness.

3 Corrosion loss measured on the soil side of the pipes.

Table 3

Averages of Estimated Years to Perforation for 16-gage Metal for all Seven Comparative Field Test Sites

Metal	Max. Cross-Section Loss	Abrasion	Corrosion
Galvanized Steel	13	21	18
Aluminum	4.8	1.9	8.6
Estimated* Average Years to Perforation for the Five Test Sites with pH Between 4.5 and 8.3			
Galvanized Steel	18	21	27
Aluminum	6.5	1.9	13

*Note: Test site with pH of 4.5 has a pH range of 4.5 to 6.3.

Table 4

Laboratory Corrosion - Abrasion Test Data

Test No.	Metal	Designated pH	Solution Measurements: Maximum Range of pH	Solution Measurements: Resistivity Ohm cm.	Distilled Water, Grams	Ottawa[1] Sand, Grams	Chemicals Used[2] in Test: Formula	Chemicals Used[2] in Test: Grams
3	Al	9.0	7.7-9.8	100	4000	4000	Na_2CO_3 NaCl	40 25
4	Al	8.8	8.6-9.6	100	4000	4000	$CaCO_3$ NaCl	4 25
5	Al	8.7	8.7-9.5	100	4000	4000	$CaCO_3$ NaCl	20 25
6	Al	10.5	10.3-10.7	100	4000	4000	Na_2CO_3 NaCl	60 25
7	Al	8.0	7.3-8.2	100	4000	4000	NaCl	25
8	Al	3.9	2.2-5.6	100	4000	4000	CH_3COOH NaCl	845 25
9	Al	3.6	3.5-3.9	100	4000	4000	$C_{76}H_{52}O_{46}$ NaCl	32 25
10	Al	6.3	6.2-6.4	100	4000	4000	NaOH KH_2PO_4 NaCl	1.6 4.9 25
11	Al	5.0	4.2-6.7	100	4000	4000	NaOH $K_3C_6H_5O_7H_2O$ NaCl HCl	7.47 46.04 25 30

Continued

Test No.	Metal	Designated pH	Solution Measurements: Maximum Range of pH	Solution Measurements: Resistivity Ohm cm.	Distilled Water, Grams	Ottawa[1] Sand, Grams	Chemicals Used[2] in Test: Formula	Chemicals Used[2] in Test: Grams
12	Steel + Zinc	9.2	7.9-9.8	100	4000	4000	$Na_2B_4O_7 \cdot 10H_2O$ $NaCl$	40 25
13	Steel + Zinc	6.3	6.2-6.4	100	4000	4000	$NaOH$ KH_2PO_4 $NaCl$	1.6 49 25
14	Steel	6.3	6.2-6.5	100	4000	4000	$NaOH$ KH_2PO_4 $NaCl$	1.6 49 25
15	Steel	8.8	8.6-9.3	100	4000	4000	$CaCO_3$ $NaCl$	20 25
16	Steel	7.5	7.0-8.8	100	4000	4000	$NaCl$	25
17	Steel	4.5	3.4-4.9	100	4000	4000	$C_{76}H_{52}O_{46}$ $NaCl$	32 25
18	Steel	5.2	5.1-5.6	100	4000	4000	KH_2PO_4 $NaOH$ $NaCl$	60 0.5 25
19	Steel	6.7	5.5-9.9	1000	4000	4000	$NaOH$ KH_2PO_4	0.042 5.0
20	Steel	7.5	7.2-7.9	1000	4000	4000	$NaCl$	2.2
21	Steel	9.1	8.9-9.6	1000	4000	4000	$CaCO_3$ $NaCl$	20 2.1
22	Steel	4.4	4.1-6.3	1000	10000	4000	$KHC_8H_4O_4$	20
23	Al	4.8	4.1-5.5	1000	10000	4000	$KHC_8H_4O_4$	20
24	Al	9.1	8.8-9.4	1000	4000	4000	$CaCO_3$ $NaCl$	2.0 2.0

Continued

Laboratory Corrosion - Abrasion Test Data

Test No.	Metal	Designated pH	Solution Measurements: Maximum Range of pH	Solution Measurements: Resistivity Ohm cm.	Distilled Water, Grams	Ottawa[1] Sand, Grams	Chemicals Used[2] in Test: Formula	Chemicals Used[2] in Test: Grams
25	Al	7.5	7.2-7.7	1000	4000	4000	NaCl	2.1
26	Steel	7.5	7.2-7.8	5000	10000	4000	NaCl	1.08
27	Steel	9.1	9.0-9.8	5000	10000	4000	$CaCO_3$ NaCl	40 0.5
28	Steel	7.4	7.1-7.4	1000	10000	4000	NaCl	4.4
29	Al	7.5	7.0-7.5	1000	10000	4000	NaCl	4.4
30	Al	7.5	6.8-7.9	5000	10000	4000	NaCl	0.4 to 1.0
31	Al	9.0	9.0-9.7	5000	10000	4000	NaCl $CaCO_3$	0.33 40
32	Al	7.5	6.8-8.5	1000	10000	4000	NaCl	4.1

Note: 1

NaCl	Sodium Chloride	$K_3C_6H_5O_7H_2O$	Potassium citrate
$CaCO_3$	Calcium Carbonate	NaOH	Sodium hydroxide
Na_2CO_3	Sodium carbonate	HCl	Hydrochloric acid
CH_3COOH	Acetic Acid	$KHC_8H_4O_4$	Potassium acid thalate
$C_{76}H_{52}O_{46}$	Tanic Acid	$Na_2B_4O_7.10H_2O$	Sodium tetraborate
KH_2PO_4	Potassium Phosphate		

2 Ottawa sand is: Standard Sand 20-30, ASTM designation C-190

Table 5

Laboratory Corrosion-Abrasion Test Results of Steel

Test No.	pH	Days of Test	Resis-tivity Ohm cm	Years to Perforation - 16 Gage			
				100% Weight Loss	Minimum X-Section	Abrasion Surface	Corrosion Surface
14	6.3	9.9	100	4.39	0.41	0.41	1.66
15	8.8	9.2	100	0.48	0.07	0.08	0.09
16	7.5	7.5	100	0.21	0.06	0.08	0.12
17	4.5	7.9	100	0.24	0.16	0.27	0.58
18	5.2	10.6	100	1.76	0.11	0.25	0.13
19	6.7	7.8	1000	1.76	0.24	0.52	0.37
20	7.5	7.7	1000	0.18	0.09	0.14	0.14
21	9.1	10.1	1000	0.98	0.11	0.17	0.15
22	4.4	8.0	1000	0.22	0.38	0.54	0.74
26	7.5	7.8	5000	3.24	0.20	0.29	0.24
27	9.1	7.8	5000	1.05	0.44	1.31	1.31
28	7.4	8.6	1000	0.53	0.10	0.11	0.18

Notes: No galvanized steel used in this test. Except for perforation by weight loss, all test results are based upon metallographic analysis of samples. Abrasion surface is the upstream side of the corrugation. Corrosion is downstream side or valley of corrugation.

Table 6

Laboratory Corrosion-Abrasion Test Results of Aluminum

Test No.	pH	Days of Test	Resis-tivity Ohm cm	Years to Perforation - 16 Gage			
				100% Weight Loss	Minimum X-Section	Abrasion Surface	Corrosion Surface
3	9.0	15.6	100	4.22	0.47	0.86	0.47
4	8.8	14.9	100	0.53	0.70	0.81	1.63
5	8.7	6.8	100	3.01	0.56	0.45	0.56
6	10.5	9.1	100	0.12	0.10	0.20	0.12
7	8.0	9.8	100	2.34	0.46	0.46	1.07
8	3.9	3.6	100	0.34	0.09	0.17	0.14
9	3.6	7.3	100	0.75	0.20	0.30	0.34
10	6.3	7.9	100	2.22	0.43	0.52	1.30
11	5.0	7.7	100	0.24	0.23	0.36	0.36
23	4.8	7.8	1000	1.36	0.23	0.29	1.28
24	9.1	7.8	1000	1.14	0.43	0.26	1.29
25	7.5	10.0	1000	2.48	0.41	0.41	0.82
29	7.5	9.9	1000	1.92	0.36	0.40	1.08
32	7.5	36.2	1000	3.24	0.91	1.32	1.48
30	7.5	8.3	5000	1.62	0.34	0.34	0.68
31	9.0	7.6	5000	0.94	0.19	0.19	0.84

Note: Except for perforation by weight loss, all test results are based upon metallographic analysis of samples. Cladding was penetrated on abrasion surface in all tests. Abrasion surface is the upstream side of the corrugation. Corrosion surface is the downstream side or the valley of the corrugation.

Table 8

Solutions Used in the Continuous Submersion Tests

Test No.	pH	Resistivity Ohm cm.	Grams of Tap Water	Chemicals Used	Grams of Chemicals
1	4.3	1000	10000	Potassium Acid Thalate ($KHC_8H_4O_4$)	22
2	7.5	1000	10000	Sodium Chloride ($NaCl$)	5.2
3	9.0	1000	10000	Calcium Carbonate ($CaCO_3$) Sodium Chloride ($NaCl$)	10 5.0

Table 9

Chemical Analysis of Sacramento City Tap Water

Total Solids	Hardness	Alk.	Cl	SO_4	Ca	Mg	Na	Fe	N	F
83 to 113	36 to 76	20 to 78	3 to 21	11 to 19	8 to 18	4 to 8	Nil	0.1	Nil	Nil

Resistivity = 8000 ohm cm
pH = 7.2
Milligrams per Liter

Chemical analysis from California Domestic Water Supplies, State of California, Department of Public Health, 1962

Table 10

Results of Continuous Submersion Test*

Estimated Years to Perforation for 16-gage Metal

Metal	Sample	pH	Years
Galvanized Steel	1	4.3	Steel was Unaffected
	2	4.3	"
Aluminum	1	4.3	2.9
	2	4.3	2.9
Galvanized Steel	1	7.5	Steel was unaffected
	2	7.5	"
Aluminum	1	7.5	2.9
	2	7.5	3.7
Galvanized Steel	1	9.0	Steel was unaffected
	2	9.0	"
Aluminum	1	9.0	2.9
	2	9.0	3.3

*Test solutions had a resistivity of 1000 ohm cm. and test period was 70 days.

Table 11

Results of Fog Room Test*

Metal	Sample	Days of Test	Years to Perforation**
Galvanized Steel	1	±365	Steel was unaffected. (Sample was from previous testing.)
Aluminum	1 2 3	94 94 94	3.2 3.2 3.2

* Fog room is room at 73.4°F, 100% R.H. and is normally used for the curing of concrete specimens. The pH and resistivity of the fogged water was 8.2 and 6300 ohm cm respectively.

**Estimated Years to Perforation for 16-gage Metal

Table 12

Nation-wide Field Test Results of Aluminum Culverts[1]

Reported Culvert Condition	Average Acid pH	Average Alkaline pH	Mean[2] Resistivity Ohm cm	Estimated[3] Rate of Corrosion	Average Acid, pH	Average Alkaline pH	Mean[2] Resistivity Ohm cm
Unaffected	6.2	7.9	2100	Nil	6.0	7.8	3100
Staining	5.9	7.7	3300				
Etching	5.5	8.0	600	Light to Moderate	5.6	7.8	2000
Pitting	5.7	7.7	4700				
Cladding Removed	2.8	---	150	Severe	3.0	---	250
Perforated	3.1	---	300				

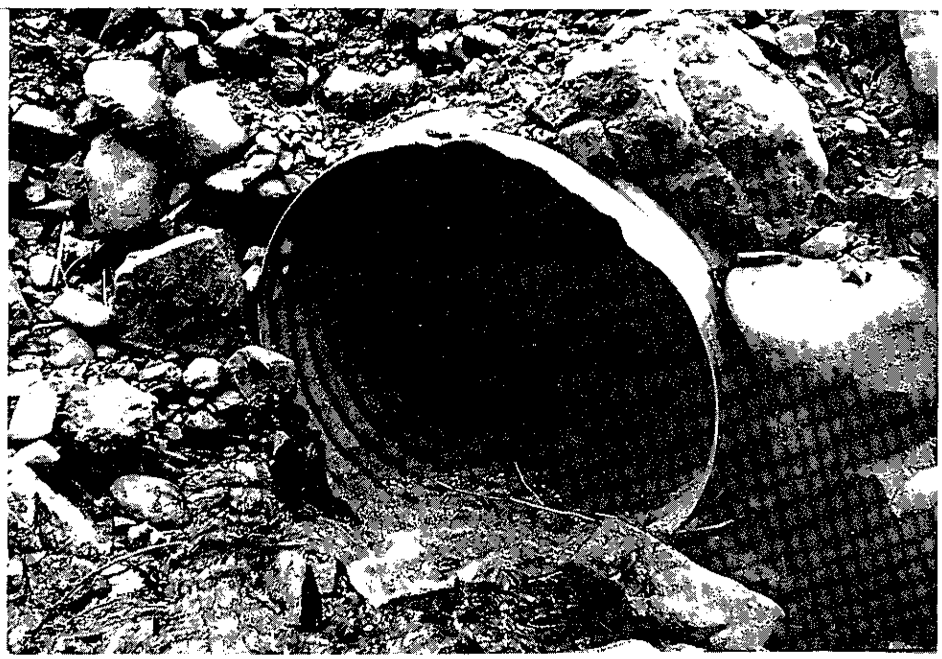
Notes: 1 Data obtained from "Corrosion Performance of Aluminum Culvert" by T. A. Lowe and A. H. Koepf, a paper presented before the 43rd Annual Meeting, Highway Research Board, January 13-17, 1964, Washington, D. C.

2 Geometric Mean

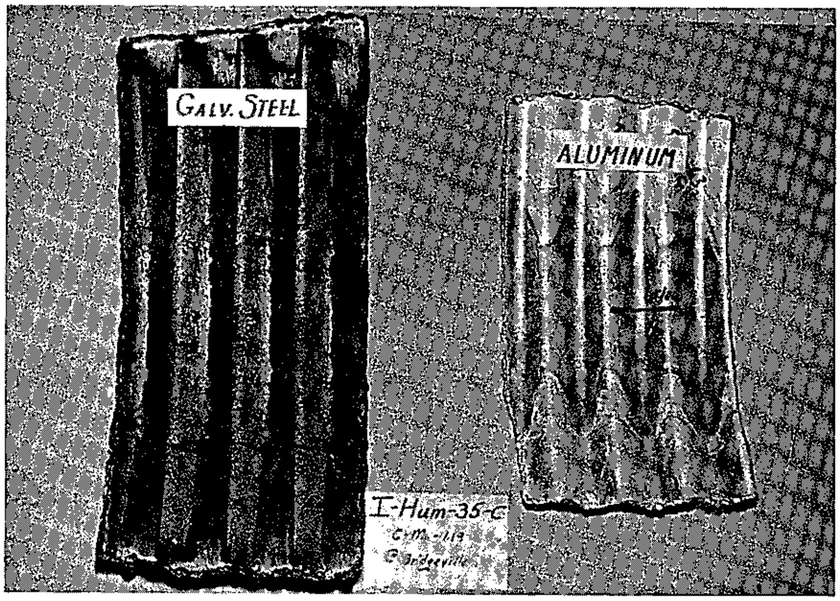
3 This estimate is speculation. The estimated rate of corrosion is entirely based upon the terminology that was used in the report for describing the visual appearance of the culverts. No rates of corrosion were reported.

Maximum years of service of reported culverts was 3.5.

Field Test Site
I-Hum-35-C, Mile 1.19

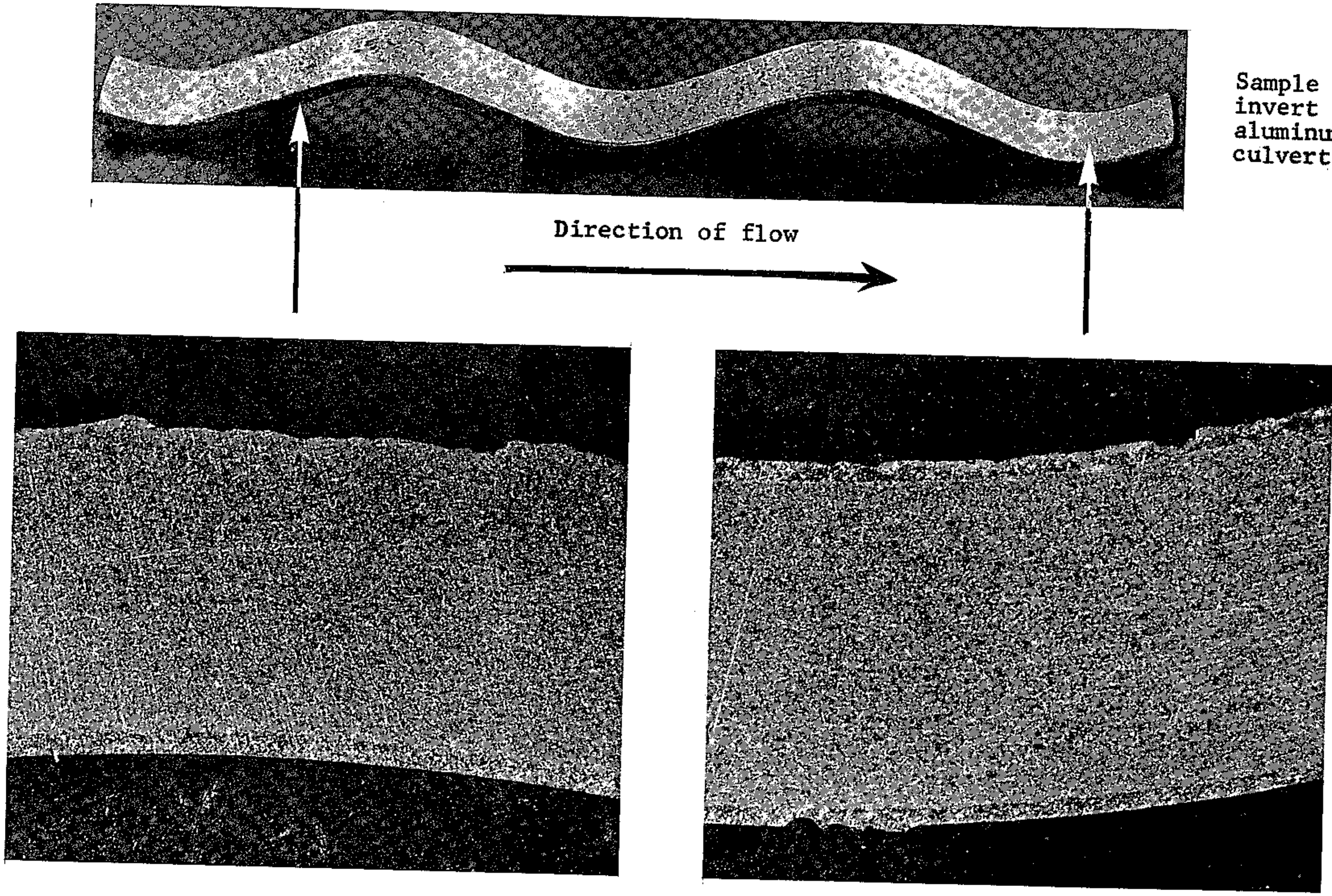


Inlet of test pipe - aluminum section



Samples removed from invert after 2-year exposure

Field Test Site
I-Hum-35-C, Mile 1.19

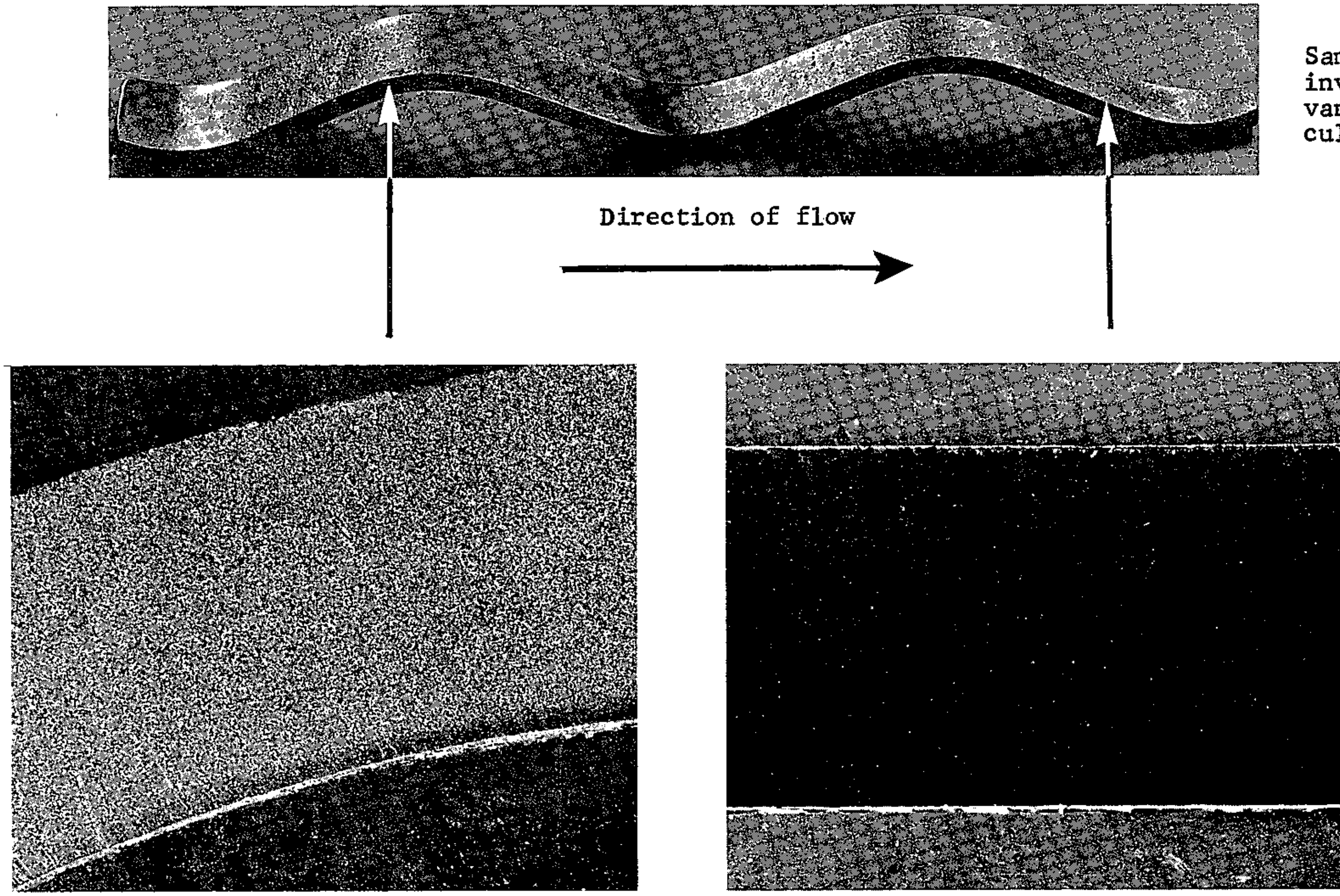


Sample from invert of aluminum culvert

Typical loss of cladding at abrasion surface - 2 years

Cladding intact - 2 years

Field Test Site
I-Hum-35-C, Mile 1.19



Sample from invert of galvanized steel culvert

20±X

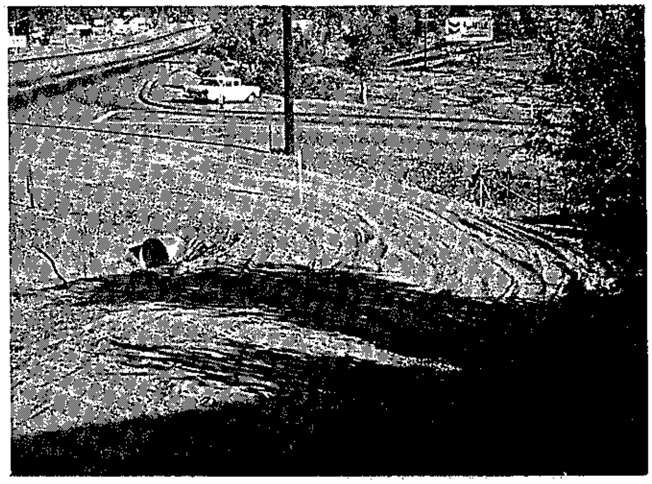
Note loss of zinc and minor loss of steel at abrasion surface - 2 years

20±X

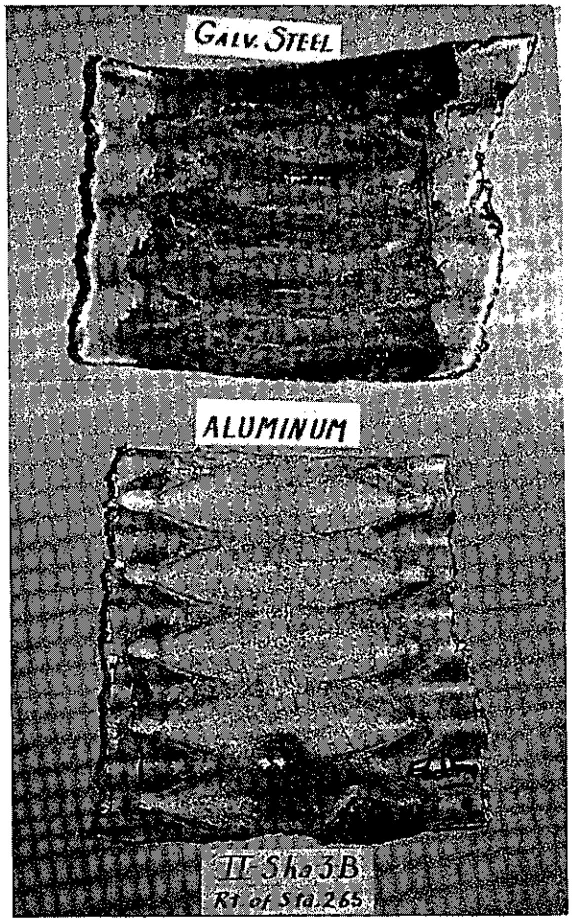
Zinc abraded but intact. 2 years

Figure 3

II-Sha-3-B
Right of Station 265±

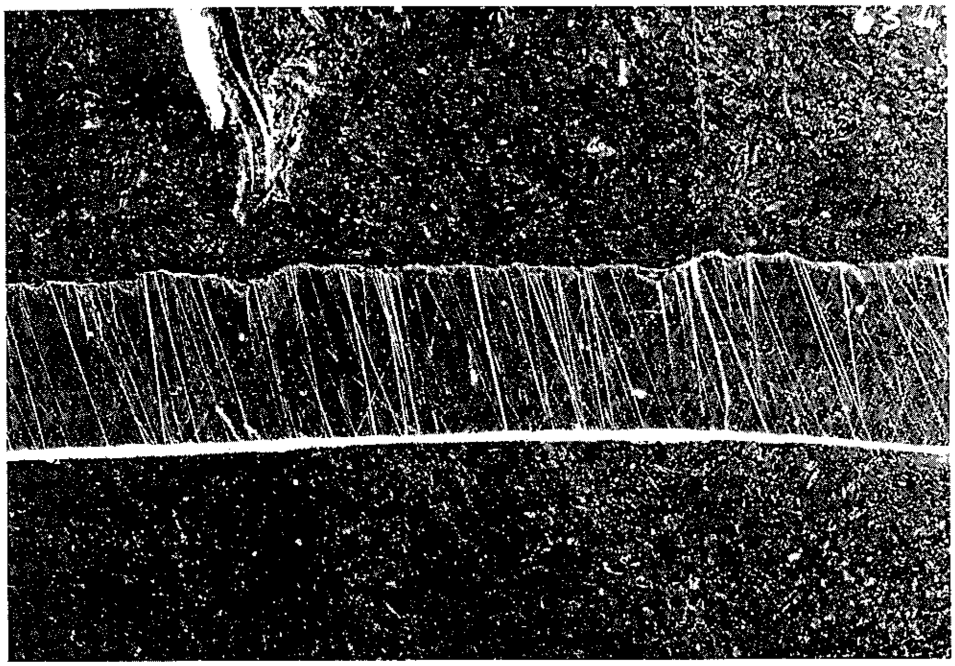


Field Test Site



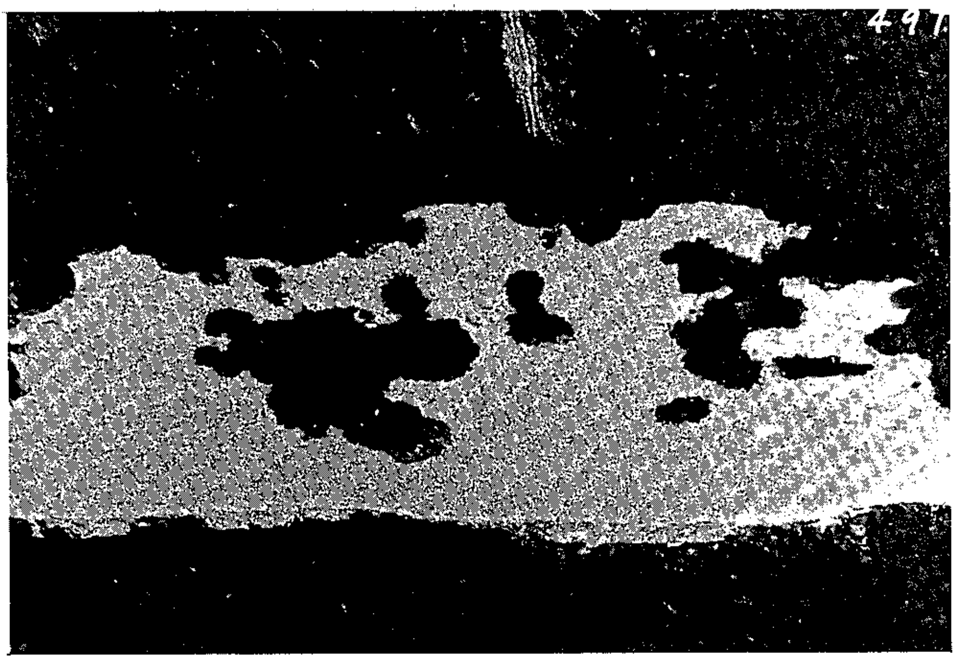
Typical invert samples removed after approximately 1.5 years of test

II-Sha-3-B
Right of Station 265±



Cross-section of steel after 1.5 years of test

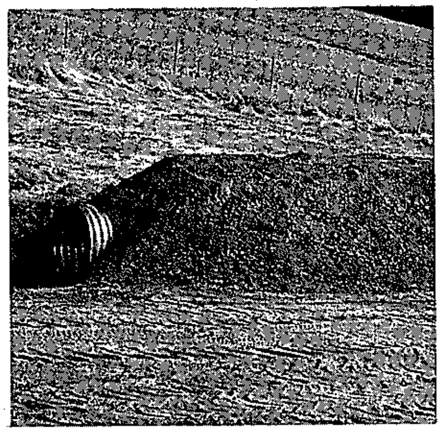
20±X



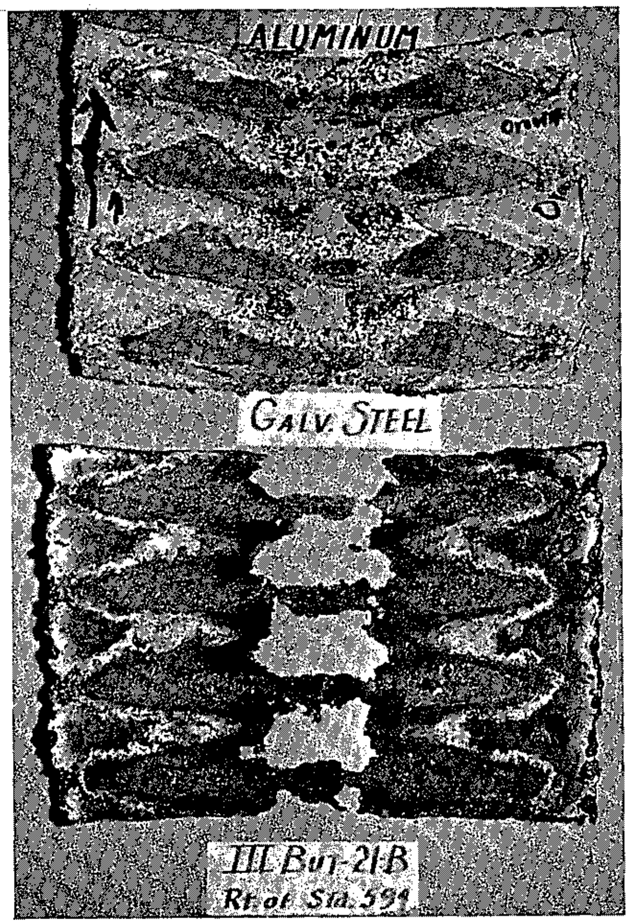
Cross-section of aluminum

20±X

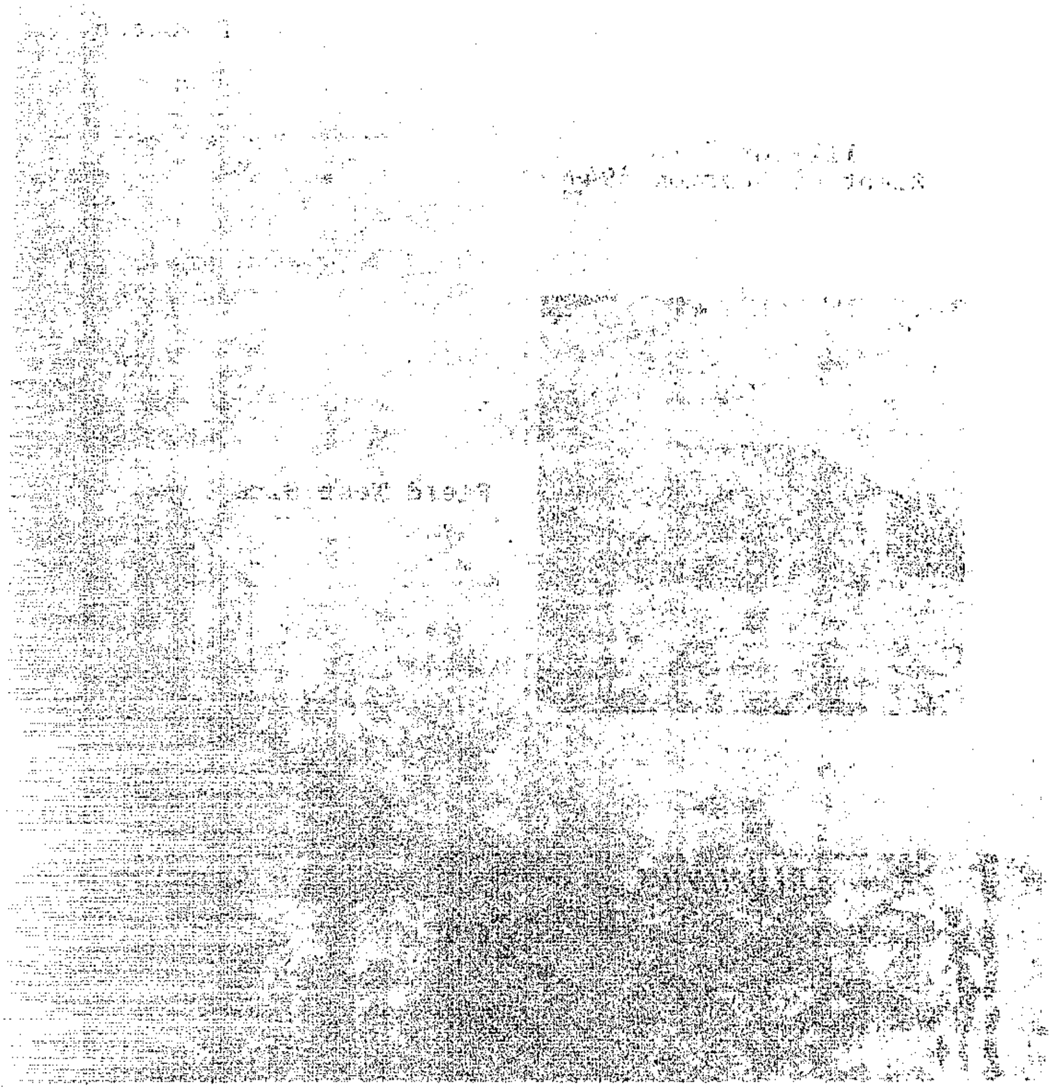
III-But-21-B
Right of Station 594±

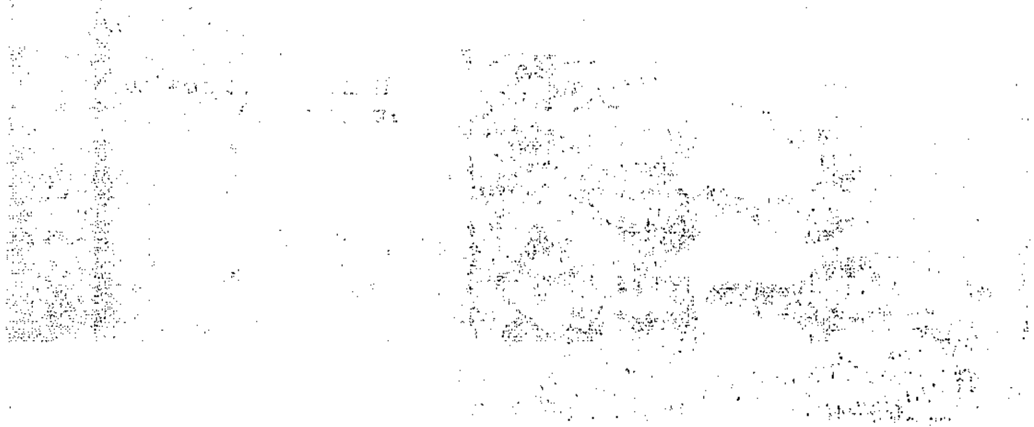


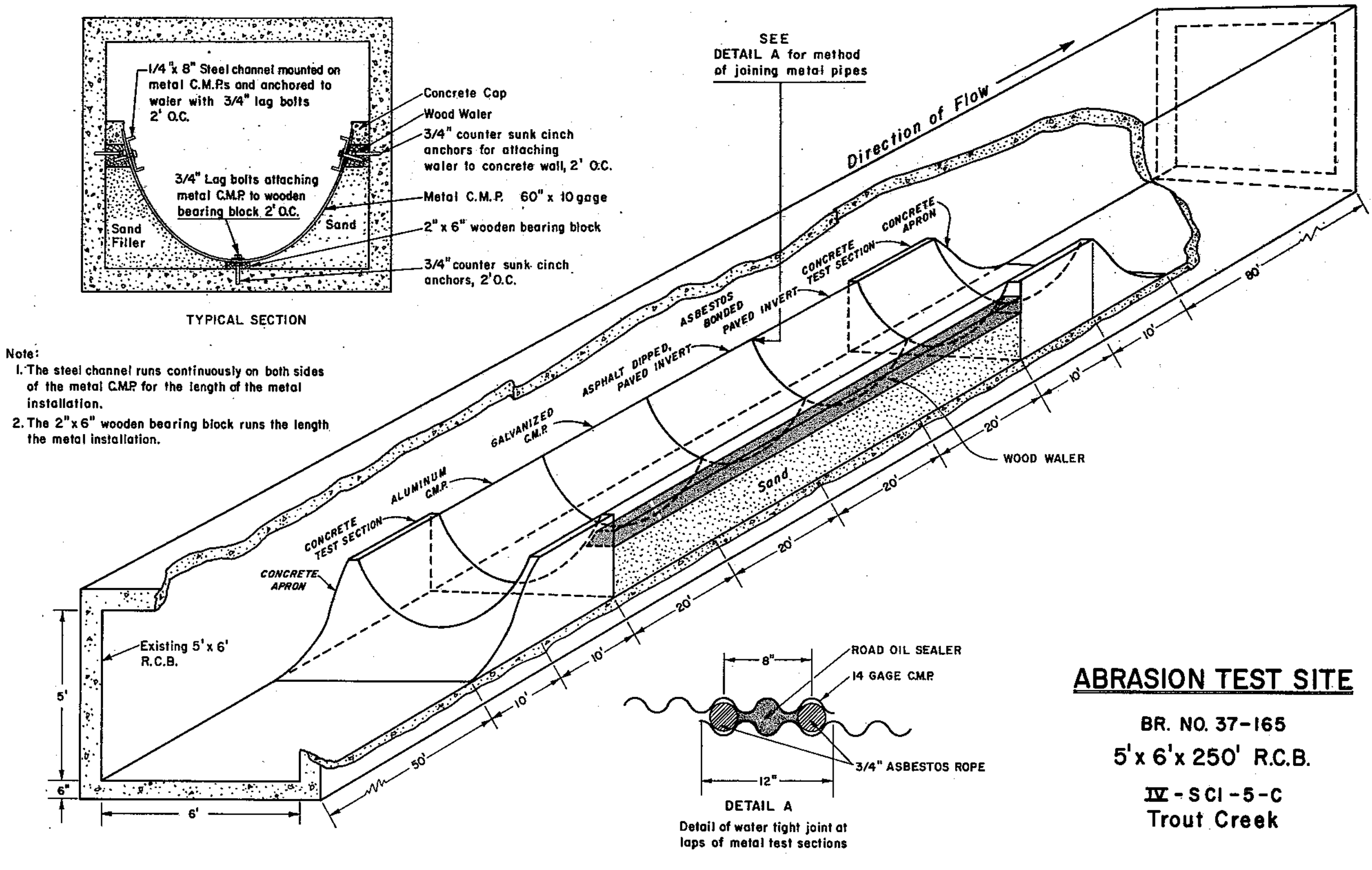
Field Test Site



Invert samples removed after approximately 1.7 years of test. (Highly corrosive exposure.)







ABRASION TEST SITE

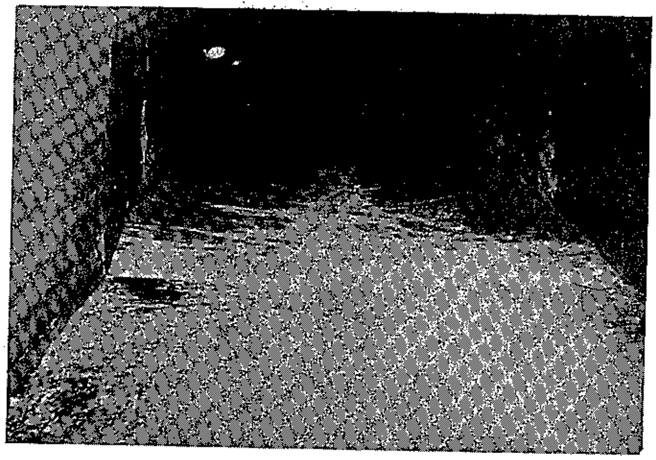
BR. NO. 37-165

5' x 6' x 250' R.C.B.

IV - SCI - 5 - C

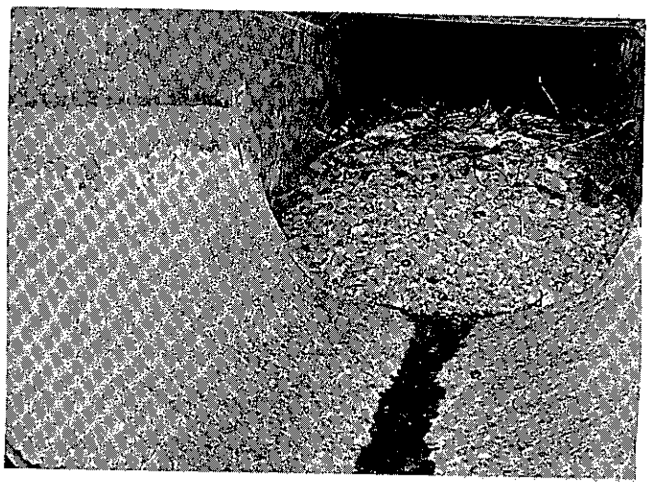
Trout Creek

Abrasion Test Site
IV-SC1-5-C Sta. 250+25
Bridge No. 37-165



"As built" concrete test section at inlet section of test culvert

Appearance of concrete test section after 1.4 years of service showing severe abrasion

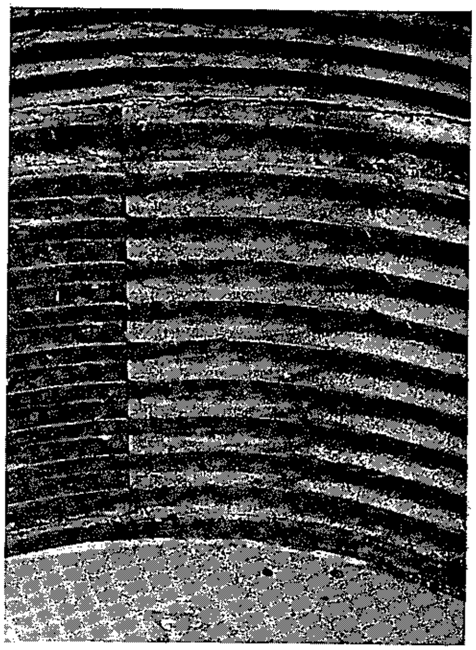


View showing loss of approximately 1/2-inch of concrete in the concrete test section at the outlet

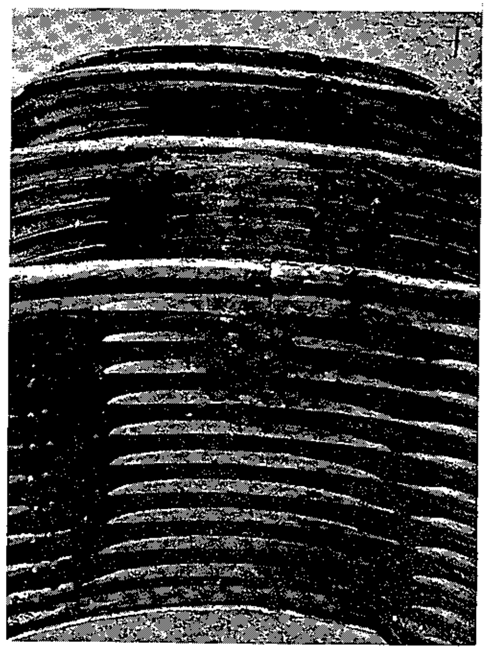
Note deposit of debris at grade change of culvert

Abrasion Test Site

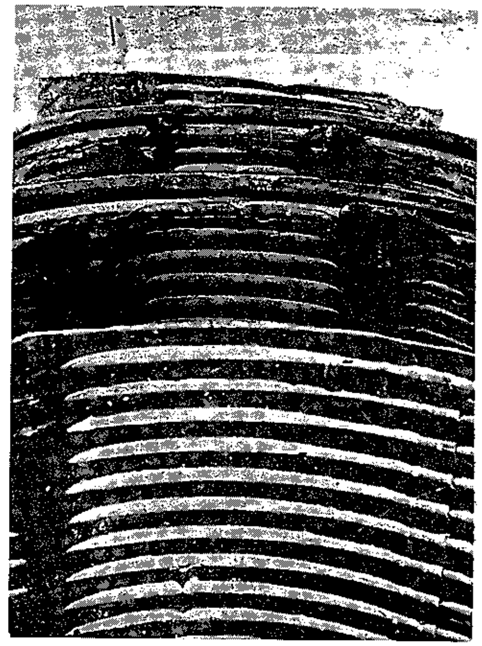
IV-SC1-5-C Sta. 250+25
Bridge No. 37-165



Samples of the invert galvanized steel section. Note wear of rivet heads.



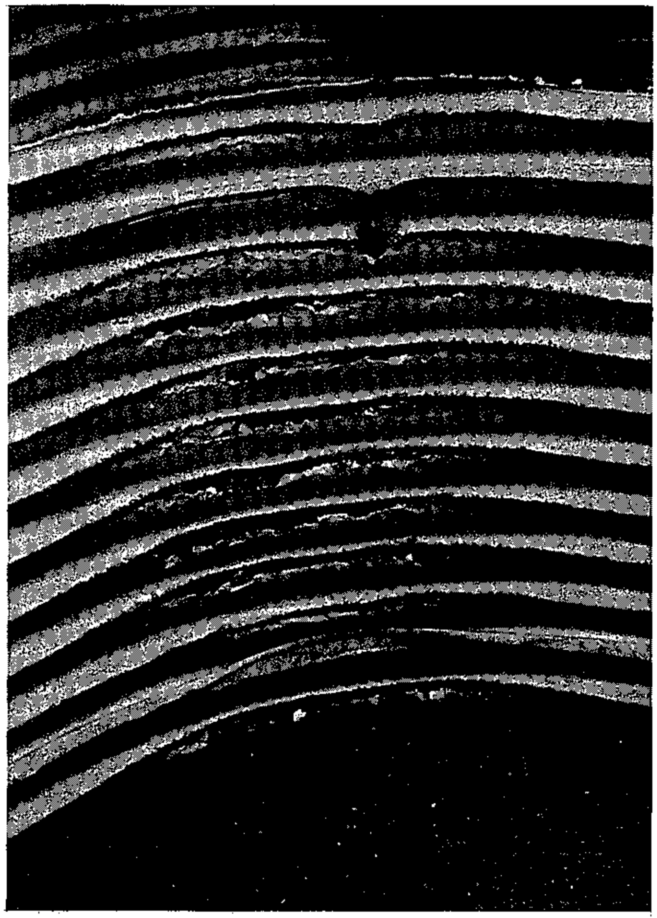
Samples of the invert from the A.D.P.I. section. Note loss of rivets at the joint.



Samples of the invert from A.B.A.D.P.I. section.

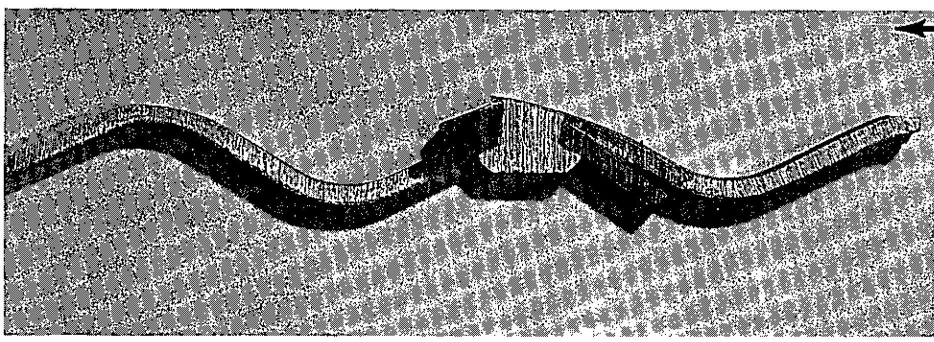
Abrasion Test Site

IV-SC1-5-C Sta. 250+25
Bridge No. 37-165



Severe abrasion of aluminum after 1.4 years of service

Direction of flow



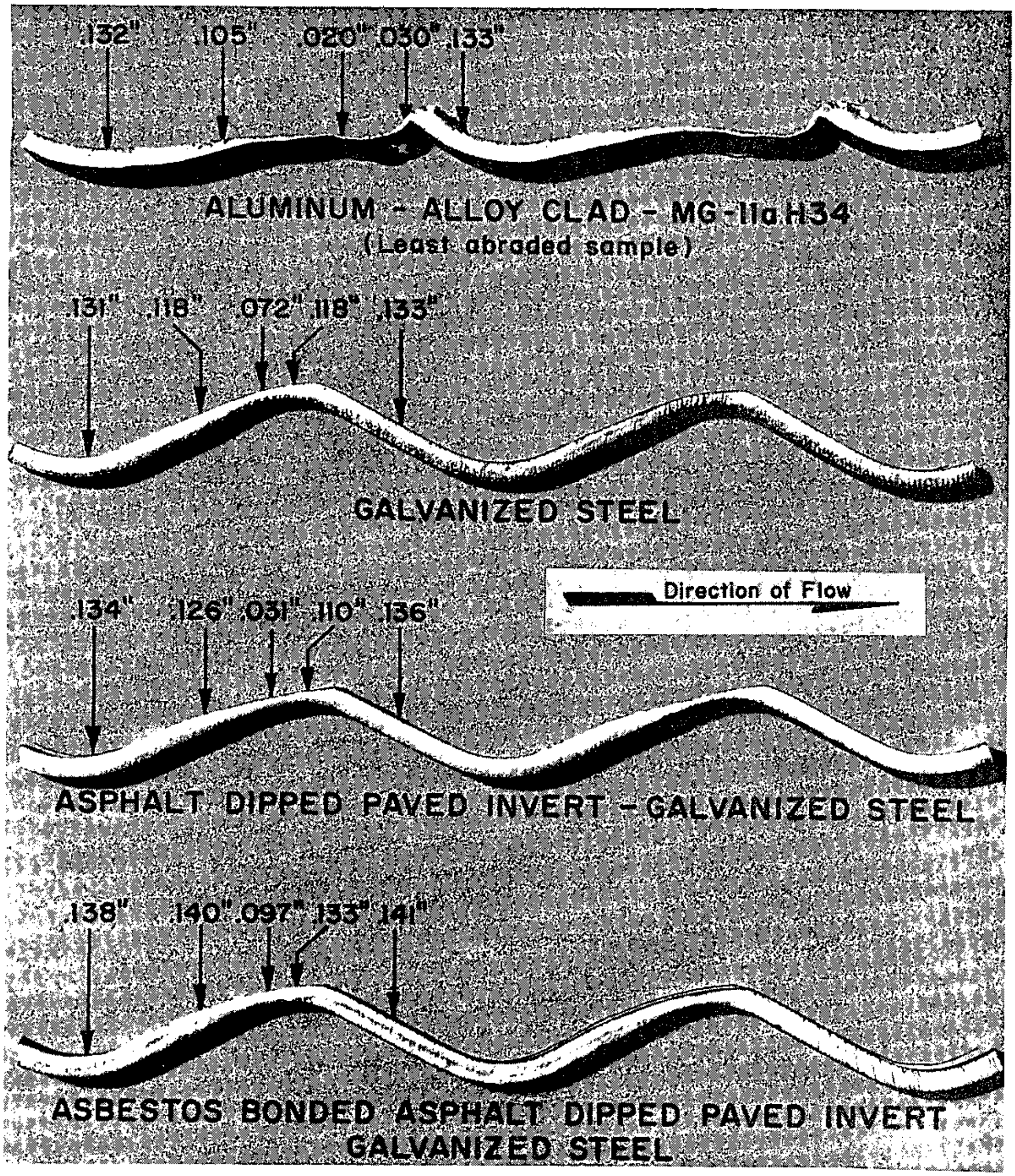
Severe abrasion of galvanized steel after 1.4 years of service. Note loss of head of rivet.

Results of Abrasion Tests

IV-SC1-5-C Sta. 250+25

Bridge No. 37-165

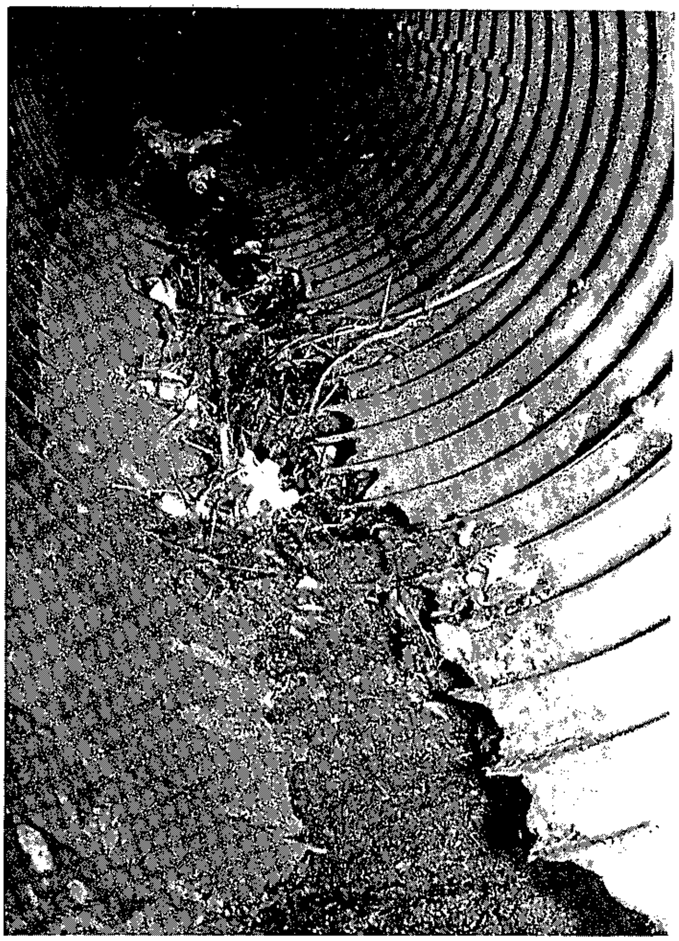
Typical cross-sections of pipe invert after test exposure.



Note: All C.M.P. samples were 10 gage (0.140±)
Steel samples are typical of the most abraded pipe sections

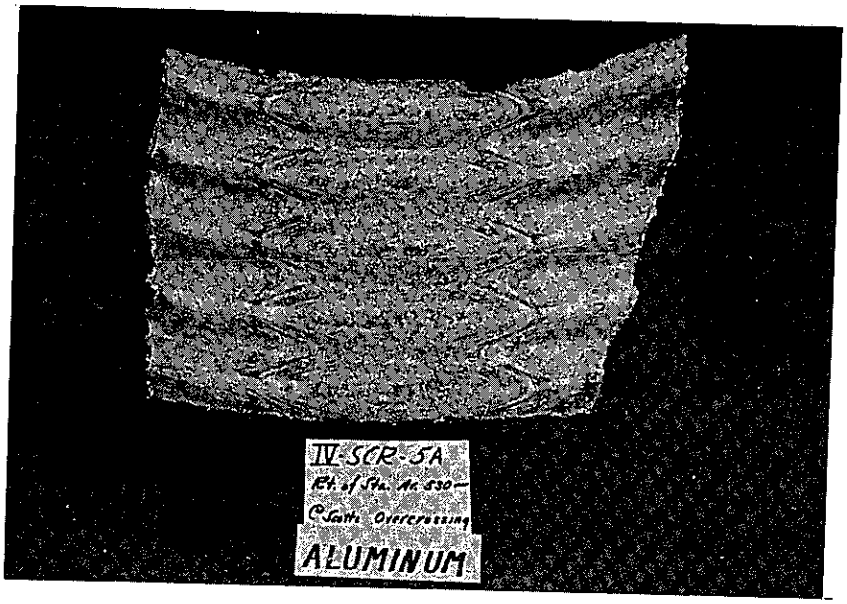
IV-SCr-5-A
Right of Station 530±

Aluminum culvert, field test site. (Exposed pipe subsequently backfilled.)

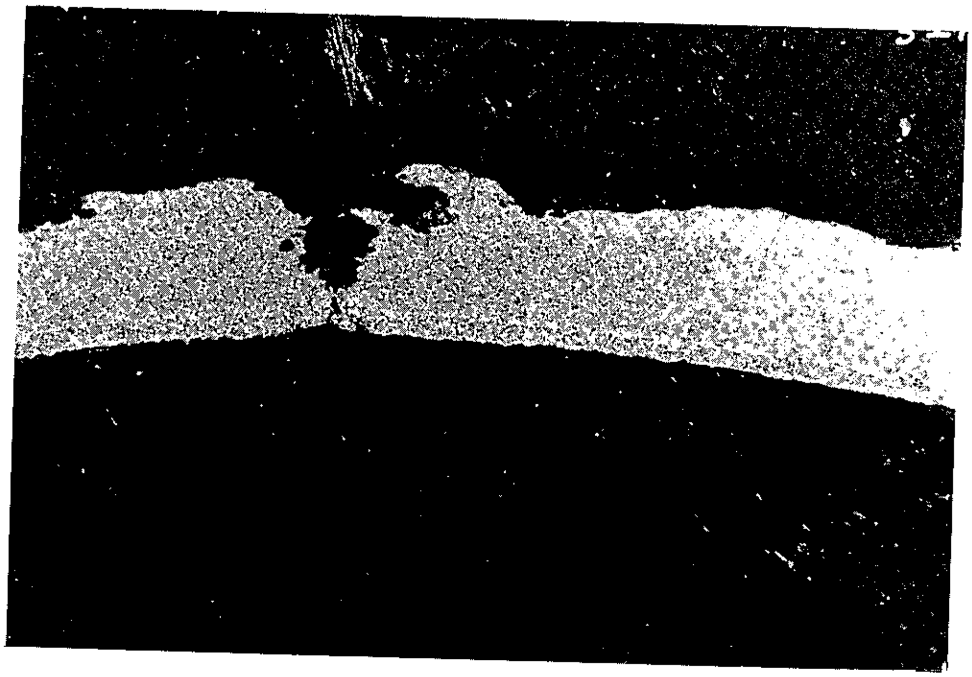


Existing galvanized C.M.P. Approximately 2 years of service. (Not placed as part of test program.)

IV-SCr-5-A
Right of Station 530$\pm$



Aluminum invert sample after approximately 0.8 years of test.

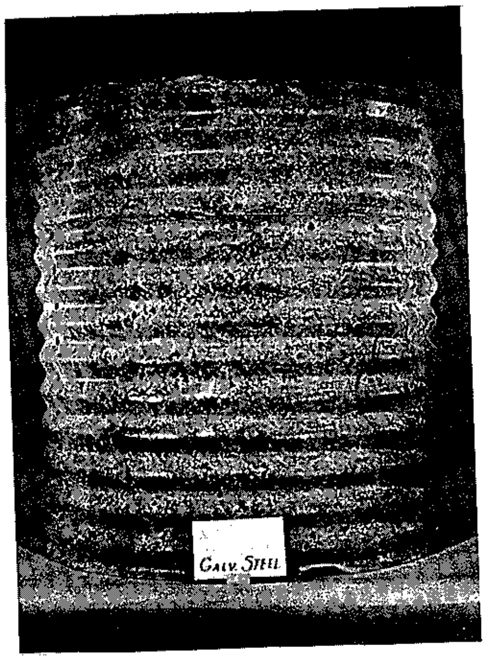


Cross-section of aluminum. Non-perforated section.

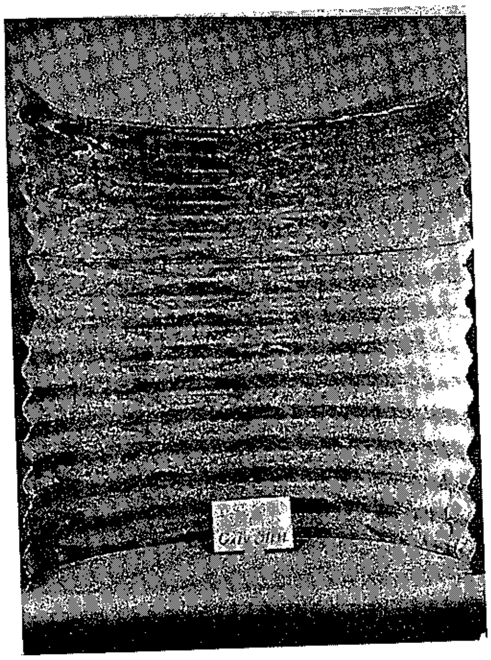
20$\pm$X

X-S.J-53-C
Right of Station 6±

Field Test Site



Backfill Side



Inside (Invert)

Appearance of cleaned galvanized steel samples after 2.4 years of test.